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# A Methodology for Compensating Errors Detected by Process-Intermittent Inspection

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## ABSTRACT

This report describes principles and methodology for compensating geometric errors of machined parts due to machining processes. The error tendencies are identified by on-machine inspection of the part before the finish cut. Tool path adjustments compensate errors anticipated in the finish cut. The methodology was validated on a prototype system implemented using the Process-Intermittent Error Compensation Software (PIECS) on a turning center.

Process-intermittent gauging of a semifinished part is directed by the machine tool controller, thus detecting only errors due to tool setting, tool wear, tool deflection or part deflection. These *process errors* are distinguished from errors caused by machine tool geometry, which are identifiable only by inspection independent of the machine tool. For process errors, an error vector is defined as having its head at the measured coordinates of a gauged point, and its tail at the nominal coordinate for that point. Least squares curve fitting through the heads of the error vectors is used to determine the error profile, from which the adjusted tool path for the finish cut is derived. Errors on a feature with a nominally straight profile are compensated by adjusting the feature's position, orientation and scale. Spline functions are used to fit errors on curved parts. At an intersection between an arc profile and a line profile, boundary conditions are imposed to maintain any required tangency between features.

In the prototype system, errors may be compensated using either of two options. The first option makes use of an error specification file containing the error profile for each feature. The tool position is monitored during finish cut machining, and machine tool servo commands are adjusted in real time to control the tool path. Or, alternatively, new tool path values can be calculated and inserted in a template to create a new part program to compensate errors for the finish cut.



**Key Words**: error; error compensation; machine tool; part; part program; process-intermittent inspection; quality control; real-time; tool path

## Table of Contents

**1. Introduction** ..... 6

**2. Process-Intermittent Error Compensation Method Overview** ..... 9

2.1 The Process-Intermittent Error Compensation Principle ..... 12
2.2 Formulating Compensation Curves ..... 16

**3. Implementation of Process-Intermittent Error Compensation** ..... 19

3.1 Management of Part Feature Data ..... 19
3.2 Compensation Calculations for Features with Linear Profiles ..... 19
3.3 Compensation Calculations for Features with Circular Arc Profiles ..... 20
3.4 Producing the Error-Compensated Tool Path ..... 20

**4. System Prototype** ..... 22

4.1 Hardware ..... 22
4.2 Software Capability ..... 24
4.3 Data Storage and Transfer ..... 24

**5. Verification Cutting Tests** ..... 26

5.1 A Part with Only Orthogonal Linear Features (FACETST) ..... 27
5.2 A Part with a Curved Feature Requiring Tangency at End (MODBAS2) ..... 35
5.3 A Part with a Curved Feature Requiring Non-Tangency at End (PIECS11) ..... 39

**6. Conclusion** ..... 42

**7. References** ..... 44

**APPENDIX: NC Programs for Test Part Machining** ..... 47

A.1. Important Commands for Rough Cutting ..... 47
A.1.1. The G02 Clockwise Circular Interpolation Mode for Arc Programming ..... 47
A.1.2. The G81 Longitudinal Turning Canned Cycle ..... 48
A.2. FACETST Part NC Programs ..... 48
A.2.1. Rough Cut NC Program for the FACETST Part ..... 48
A.2.2. Semifinish Cut NC Program for the FACETST Part ..... 49
A.2.3. Finish Cut NC Programs for the FACETST part ..... 51
A.3. MODBAS2 Part NC Programs ..... 52
A.3.1. Rough Cut NC Program for the MODBAS2 Part ..... 52
A.3.2. Semifinish Cut NC Program for the MODBAS2 Part ..... 54
A.3.3. Finish Cut NC Program for the MODBAS2 Part ..... 55

A.3.4. Pre-Semifinish Cut Program for the MODBAS2 Part .....56
A.4. PIECS11 Part NC Programs .....58
A.4.1. Rough Cut NC Program for the PIECS11 Part .....58
A.4.2. Semifinish Cut and Finish Cut NC Programs for the PIECS11 Part .....60
A.4.2.1. First Part in the PIECS11 Family, Semifinish Cut Points .....61
A.4.2.2. First Part in the PIECS11 Family, Semifinish Cut Program .....61
A.4.2.3. First Part in the PIECS11 Family, Finish Cut Points .....62
A.4.2.4. First Part in the PIECS11 Family, Finish Cut Program .....63
A.4.2.5. Second Part in the PIECS11 Family, Semifinish Cut Points .....64
A.4.2.6. Second Part in the PIECS11 Family, Semifinish Cut Program .....65
A.4.2.7. Second Part in the PIECS11 Family, Finish Cut Points .....66
A.4.2.8. Second Part in the PIECS11 Family, Finish Cut Program .....66
A.4.2.9. Third Part in the PIECS11 Family, Semifinish Cut Points .....67
A.4.2.10. Third Part in the PIECS11 Family, Semifinish Cut Program .....68
A.4.2.11. Third Part in the PIECS11 Family, Finish Cut Points .....69
A.4.2.12. Third Part in the PIECS11 Family, Finish Cut Program .....70
A.4.2.13. Fourth Part in the PIECS11 Family, Semifinish Cut Points .....71
A.4.2.14. Fourth Part in the PIECS11 Family, Semifinish Cut Program .....72
A.4.2.15. Fourth Part in the PIECS11 Family, Finish Cut Points .....73
A.4.2.16. Fourth Part in the PIECS11 Family, Finish Cut Program .....73
A.4.2.17. Fifth Part in the PIECS11 Family, Semifinish Cut Points .....74
A.4.2.18. Fifth Part in the PIECS11 Family, Semifinish Cut Program .....75
A.4.2.19. Fifth Part in the PIECS11 Family, Finish Cut Points .....76
A.4.2.20. Fifth Part in the PIECS11 Family, Finish Cut Program .....77

## 1.0 Introduction

Inspection of machined parts is no longer separated from fabrication. In-process gauging is gaining wider acceptance, since it has been recognized for some time that the best estimation of a machine's ability to produce a particular part contour is obtained by on-machine dimensional measurements [1]. The machine tool itself has been proven to be a practical measuring instrument [2]. In fact, standards have been developed to evaluate the performance of machine tools as measuring machines [3, 4]. Process-intermittent workpiece measurement on NC machines using commercial devices, such as touch trigger probes, was conceptually described in the early 80's [5]. Commercial devices for on-machine gauging are now widely available. In-process gauging along with thermal sensing can now be used to compensate errors introduced in the machining process as described in [6].

Although there has been a history of in-process measurement, monitoring and control many methods are experimental and do not make use of commercial on-machine gauges. Shiraishi [7] has surveyed in-process techniques for dimension, profile and surface roughness measurements from 1964 to 1985. Park, et al. [8] have demonstrated an in-process laser-based control system for flatness. Kohno, et al. [9] have experimented with a precision form accuracy control system for turning based upon a non-contact workpiece surface sensor. Shiraishi and Sato [10] have developed a technique to control both dimension and surface roughness during turning. Li and Li [11] have developed a technique for roundness error compensation by using a laser beam reflected from the tool post to a photo sensor detector. Ni and Wu [12] use a multiple-degree-of-freedom laser optical system to perform volumetric error compensation. Fan and Chao [13] developed an in-process workpiece dimension measurement and error compensation technique for turning that uses three servo measurement units. On-machine optical methods have been used for shape measurement of workpieces by several researchers. Dinauer, et al. [14] tested four algorithms for removing shape and waviness in sculpted surface production processes by using an optical probe to scan their ground surfaces. Fizeau and zone-plate interferometry have been used in manufacturing of high precision spherical and aspherical workpieces by Nomura, et al. [15, 16]. Nobel, et al. [17] have used a vision system to measure the tool nose form and used this information to compensate during a finish cut.

The previous researchers have shown the complexity involved with developing in-process measurement and control systems at the machine level. Other researchers have attempted to assimilate CAD (Computer-Aided Design) and CAM (Computer-Aided Manufacturing) software packages into integrated machining systems. Chow and Sakal [18] describe the integration of two commercial CAD and CAM packages using computer-aided process planning. Fan, et al. [19] describe an integrated system that has similar characteristics to the one described in the current report. They describe process-intermittent compensation of machine geometric errors for certain types of 3D parts on a milling machine after having reached thermal equilibrium. They employ CAD-interactive generation of on-machine probing paths along with commercial touch-trigger probing of the part. They do not use curve fitting to model errors but use two end points to define a line and plane errors are determined by one point. Intersections and relations between features are not considered.

An earlier report by Bandy and Gilsinn [20] describes the Process-Intermittent Error Compensation Software (PIECS) process for turned parts with profiles consisting of only linear features. A similar method was experimentally applied to circular arcs, but without constraints on the feature end points [21]. The current report extends the software capabilities of the previous work to include parts with profiles that include circular arcs requiring both tangency and non-tangency relationships with neighboring features. This report describes an integrated system for implementing compensation of errors detected by process-intermittent gauging due, for example, to inaccurately specified tool dimensions, tool wear, or tool and/or part deflection. Process-intermittent gauging, as understood here, refers to inspection occurring during an interval between a semifinish and finish machining process.

This technique has some advantages over in-process measurement and control. For instance, a simple measurement device such as a touch-trigger probe may be used instead of the more intrusive apparatus required for measurement during active machining which may not function in the presence of coolant and chips. Also, since a complete profile of the error pattern may be obtained in advance of finish machining, computational filters may be applied to the compensating tool path to minimize the effects of measurement irregularities. The PIECS system developed at the National Institute of Standards and Technology (NIST) corrects complex part dimension and form errors introduced during finish machining of a part. It supports rapid process-intermittent measurements of the machined part, between the semifinish and finish machining processes, by replacing the tool with a touch trigger probe and thereby transforming the machine tool into a coordinate measuring machine. This permits on-line modeling of in-process errors in order to compensate these errors in the finish process. After the gauging process is complete the touch-trigger probe can be rotated out of position and the next appropriate tool rotated into position for the finishing process.

The PIECS software compensates the process-related errors by automatically modifying the tool path specifications (such as coordinates, tool offsets, etc.). These modifications are made to a file of tool path adjustment data that are used to correct for the anticipated errors during the machining of the finished part. The procedures supporting the modifications depend on establishing the nominal geometry of the desired part through a computer-aided design (CAD) of the part. Design feature information, on-machine inspection points, inspection probe information are all automatically stored in files that are passed to the PIECS algorithm. The differences between the part dimensions gauged by a touch-trigger probe between machining passes, and the corresponding nominal dimensions, are analyzed and weighted to produce tool path adjustments for the subsequent machining pass. The NC controller uses coordinates that are modified on the basis of error patterns observed from on-machine probing in order to make the tool traverse a path significantly closer to the ideal path.

PIECS was integrated into the Quality in Automation system, a testbed for experimenting with various error compensation strategies at NIST [22, 23, 24]. Implemented on a turning center, PIECS was demonstrated to be a feasible and successful approach to reducing process errors.

This report is divided into the following sections. Section 2 explains the principles and method used for process-intermittent error compensation. Section 3 presents the steps for implementation and operation of the prototype system. Section 4 describes the particulars of the prototype system used to test the methodology on a turning center. Section 5 gives results of three verification tests. The various NC part programs required during the verification tests are given in the Appendix.

## 2.0 Process-Intermittent Error Compensation Method Overview

Process-intermittent error compensation requires segmenting, and in some cases modifying, the original NC part program. The finish cut segment of the NC program is a template that is generated by replacing tool path coordinates with variables, and by adding variable tool offset update commands before the cutting commands. CAD-based methods facilitate the creation of pre-process data such as part feature geometry, nominal coordinates of gauging points, surface normal vectors, and the NC probing program segments.

The part is measured by on-machine gauging after a semifinish cut that uses the same cutting parameters (speed, feed and depth of cut) as will be used for the finish cut, to ensure nearly identical cutting forces and error characteristics. The part errors are calculated based on the nominal part dimensions and the calibrated length and stylus diameter of the probe used for gauging. Any discrepancy in the tool geometry will contribute to the error measured after the semifinish cut, and thus will be compensated in the finish cut. The gauging data are sent to a computer. For each gauging point, an error[1] is computed as a vector from the nominal coordinate to the detected surface. Figures 1 - 4 below show steps in the gauging operation. A touch-trigger probe is used to detect the surface of the part features at each sampled point along the feature. The part illustrated has typical features: spherical (dome), conical (taper), cylindrical, and flat. Since this report is restricted to two-axis machining of axis-symmetric parts, the features will be described in terms of their two-dimensional profiles: lines or arcs.

Least squares curve fitting is used to determine the compensating tool path curve. Either linear equations or splines are first used to fit the measured errors found in the previous step. The linear equations are used to fit errors on linear features whereas splines are used on curved features. Coordinates along the nominal tool path for a feature are adjusted—shifted by the magnitude of the calculated error vectors, but in the opposite direction. The compensation curve is thus the tool path for the corresponding feature for the finish cut. The adjusted position, orientation, form and dimensions of the feature are thus determined. For cases in which the endpoint of the tool path for a feature also serves as the start point of the tool path for the next feature, the adjusted coordinates for that point are calculated as the adjusted intersection of the error curves for the two paths. The case in which the two features must have the same slope at that intersection requires that condition as an additional constraint. If the shape of a line, contour or circular arc is found to be deformed with respect to the nominal shape, the interpolation codes in the part program may be replaced by explicit linear point-to-point paths whose endpoints may be modified accordingly. Based on this information, errors may be compensated using either of two options: (1) an error specification file may be used to compensate the errors in real time (to accomplish this, the prototype uses a smart interface to the machine tool controller); or (2) the finish cut NC program may be modified by either changing existing coordinates or replacing individual instructions with a series of corrected linear path instructions.

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[1] It is recognized that the preferred term for this definition is "deviation" rather than "error," according to the International Vocabulary of Basic and General Terms in Metrology (VIM), a publication of the International Organization for Standardization (ISO). The term "error compensation" in this report is consistent with common reference to reducing measured part size discrepancies. With terms explained prior to discussions, the authors feel that in the context of this report, the common usage of "error" has clear meaning and reads less tediously than would the proper usage of "deviation."

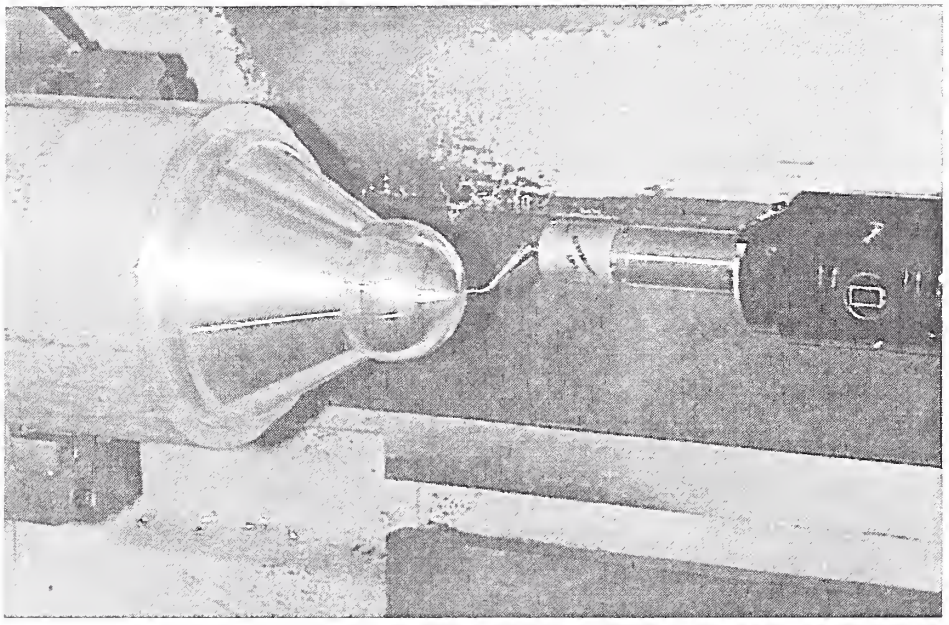


**Figure 1: Probing Part Zero**

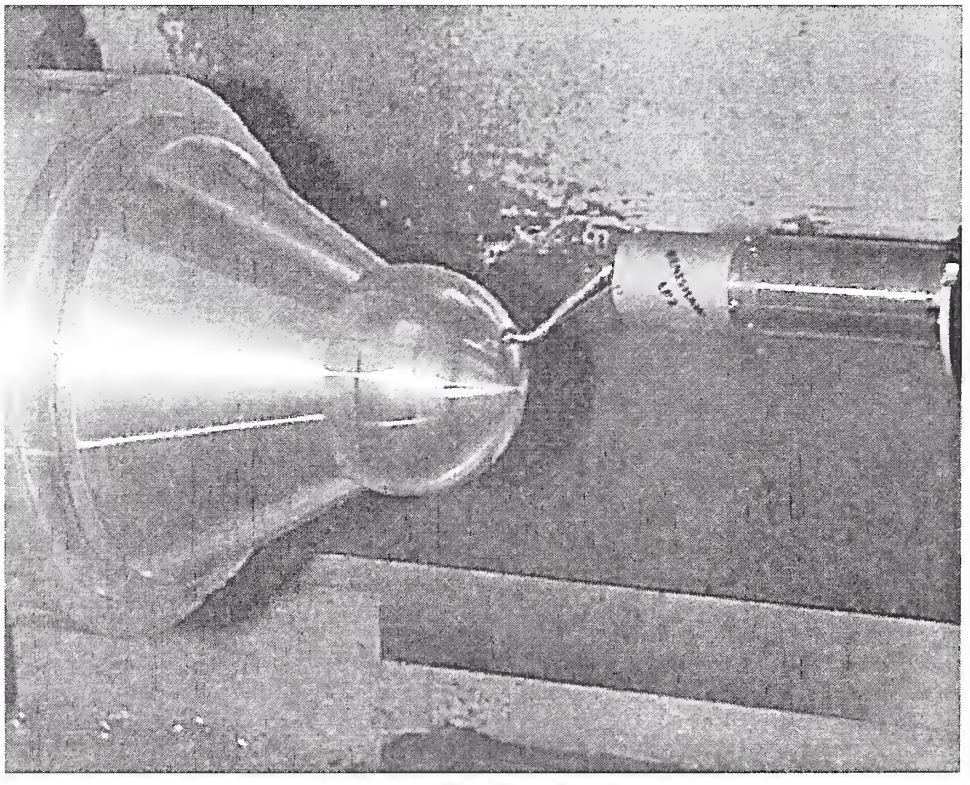


**Figure 2: Probing Along the Dome**

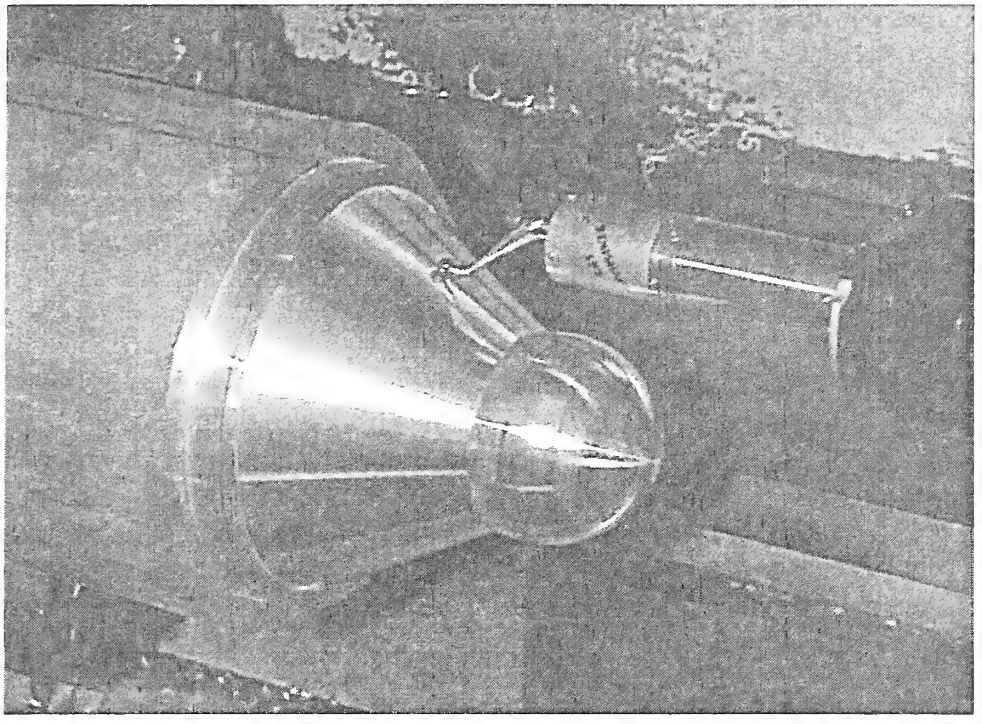


**Figure 3: Probing the Taper**

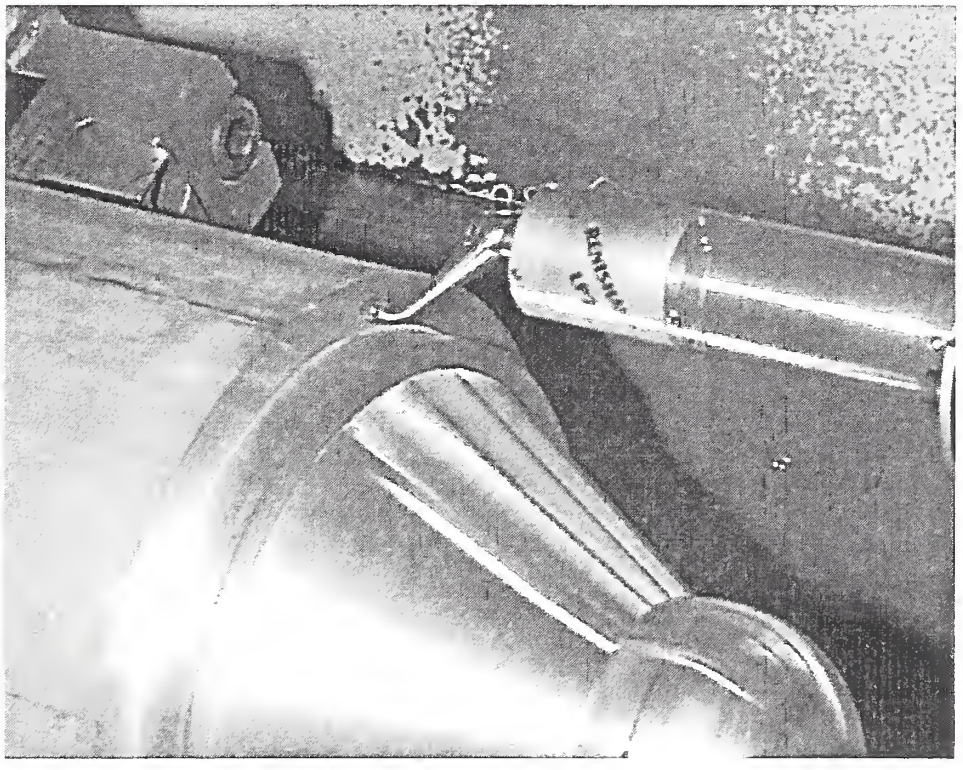


**Figure 4: Probing the Base Plane**

## 2.1 The Process-Intermittent Error Compensation Principle

Implementation of process-intermittent error compensation is a two-stage process. In the first stage, after a semifinish cut, the part is inspected, and the error pattern is determined. It is assumed that random errors are small compared to the repeatable pattern of errors addressed here. In the second stage, the finish cut is performed using an error-compensating tool path based on the error pattern. The algorithm used assesses one feature at a time, and then computes the adjusted meeting points of contiguous features for the finish cut. The process will be considered first for the simplest case, and then the logic will proceed to more general cases.

Consider the theoretical case of compensating errors on a single linear feature that is bounded on each side by a feature with which it forms a right angle. Assume that the bounding features have negligible error. In Figure 5, the horizontal solid line represents the nominal profile of the feature for the semifinished part. Theoretically, this nominal profile is achieved by the NC program segment describing the tool path for that section of the machined part. But, due to previously mentioned errors in the process, the resulting "actual" profile deviates from this nominal profile as shown in Figure 5 as the dashed line labeled *error curve.* The *compensation curve,* shown as the dotted line in Figure 5, is the modified tool path to produce an actual profile that coincides with the nominal profile. From the figure, it may be seen that the tendency to deviate from a nominal point by a certain amount is compensated by specifying a path containing a point that deviates from the nominal point by the same amount in the opposite direction.

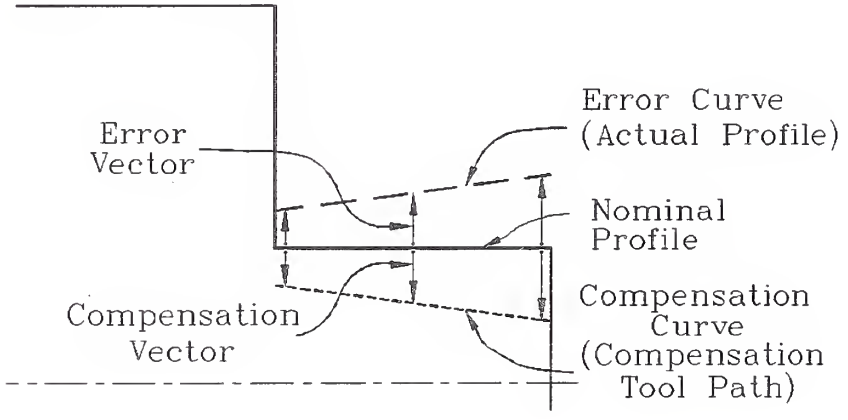



**Figure 5: Feature Error Compensation**

When the NC controller attempts to move the tool along the nominal tool path, errors may cause the actual path the tool follows to be different. The actual location of the tool when it should be at any given point along the nominal path may be found by projecting a vector from that point, in a direction normal to the nominal path, to the actual path. This is the *error vector,* defined as extending from any nominal point to the corresponding error point. The *compensation vector* is obtained by taking the mirror image of the error vector with respect to the nominal surface. Thus it points to the *compensation point* for that nominal point. The compensation curve is the locus of points at the heads of compensation vectors for all points on the nominal feature. Although this is obvious in the example case of a linear error curve, the same principle applies for arbitrarily shaped error curves, as shown in Figure 6. Of course, the curves must be extrapolated at each end, beyond the first and last inspection points.

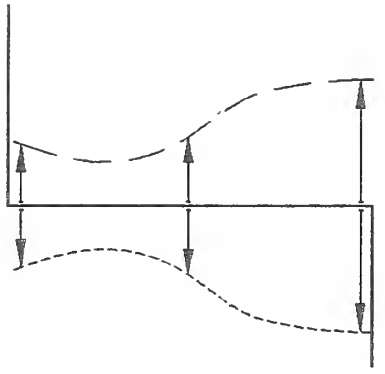


**Figure 6: Compensating Errors on a Linear Feature.**

To address the case of arbitrarily curved features with arbitrarily shaped error curves, boundary conditions for the feature endpoints must be addressed. If ends of the feature of concern do not meet the bounding features at right angles, then the errors in the bounding features must be considered. This is illustrated in Figure 7, using surface normal vectors to relate the error profile to the contour of the surface. The example illustrated is a special case in which the errors on the bounding features are constant.

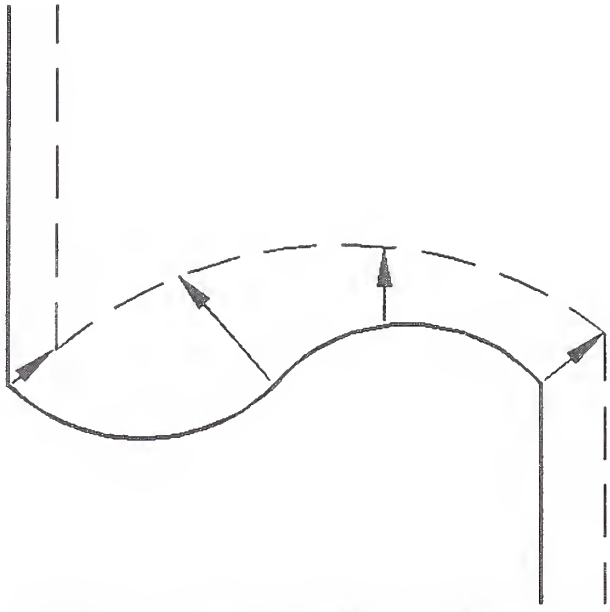


**Figure 7: Curved Feature with Boundary Errors**

The problem becomes a bit more complex in the realistic situation in which the general characterization and treatment of errors must be applied to the bounding features as well. In such a case, the intersection between the error curves of two features locates the error of the meeting point of the two nominal features. As opposed to the theoretical situations described above, the error vector at the meeting point is no longer normal to the surface. This means that the mapping of nominal points to error points may not be performed with surface normal vectors (Figure 8). But it is clear that the errors for the meeting points, since they result from intersecting error curves for two features, are applicable for both features.

For a particular feature, the start point error vector may be at some angle $\theta_s$ with respect to the surface normal vector at that point, and the end point error vector may be at angle $\theta_e$ with respect to its surface normal (Figure 9). The angle $\theta_i$ which the error vector makes with the surface normal vector at point i on the nominal feature is between $\theta_s$ and $\theta_e$, in proportion to where point i is located along the arc length of the feature. If $L_{s,i}$ is the arc length from the start point to point i, and $L_{s,e}$ is the arc length of the entire feature, then the interpolation formula is shown in Figure 9.

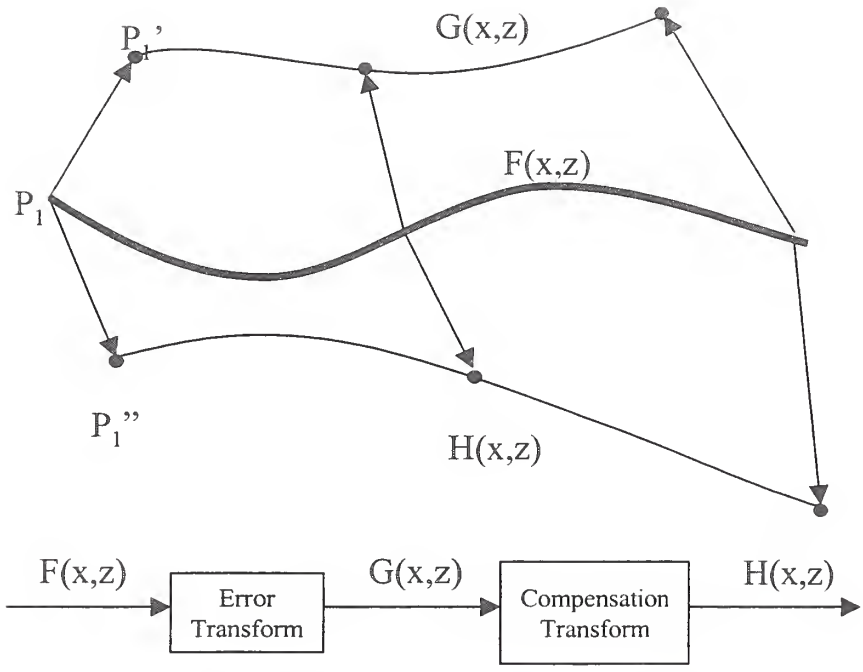
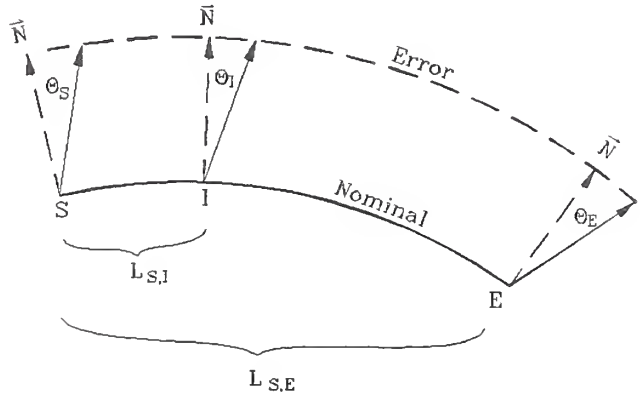



**Figure 8: Compensating Errors on an Arbitrary Feature.**




$$\Theta_I = \Theta_S + \frac{L_{S,I}}{L_{S,E}} (\Theta_E - \Theta_S)$$

**Figure 9: Mapping Nominal Points to Error Points.**

Defining the error vectors as such, the compensation curve may be derived from any error curve for any feature. The general formulation does not depend on any assumptions about adjacent features. However, the exact solution, a curve fitted to the heads of the tilted error vectors, depends on the vector angles, which are not readily known in practice.

For practical application of this principle, there is a technique for deriving an approximate compensation curve which will have no significant deviation from the exact solution. If a compensation curve based on surface normal vectors is translated, rotated and scaled such that the endpoints satisfy the boundary conditions derived from the intersections of the error curves corresponding to neighboring features, it will nearly coincide with the exact curve for the following reasons. Consider the error profile of a feature having X errors along its Z length, and having Z errors identified on the bounding feature at each end point. At every point, the approximate compensation curve will be negligibly shifted in the Z direction from the corresponding Z coordinate in the exact curve, because the difference is based only the errors at the endpoints, and are distributed over the entire X-length of the curve. And since, in practice, the errors at points that are very close together are nearly identical, the X values will be nearly exact.

## 2.2 Formulating Compensation Curves

Effective error compensation depends on accurate formulation of compensation curves. For each part feature, a curve must be calculated for a good approximate fit through the compensation points derived as stated earlier. The curve-fitting technique applied must be suitable not only for the curvature of the feature, but also for the requirements of the bounding features. To account for the possibility of significant inflections, compensation curves may be fitted with *splines*. However, the end point constraints are often dependent on the compensation curves for adjacent features.

Two cases of angular relationship arise when two features meet: non-critical and critical. The angle is critical if it is a design constraint. In a very common case for turned parts, a feature with a linear profile (such as a horizontal cylinder) meets a perpendicular feature also having a linear profile (such as a vertical face). In this case, the endpoint of one compensation curve (often adequately modeled as a least squares line) coincides with the start point of another compensation curve (another least squares line). The shared point is, of course, the intersection of the two lines, and usually, the exact angle between the two features is non-critical. In the second case, say, when an arc meets a line or another arc, it is often important that the two features maintain smooth tangency at the intersection. Tangency is perhaps the most common case of critical angular relationship between features.

If the curves for two adjacent features are fit separately, a discontinuity might result at the nominal point of tangency. In the finish cut this could lead to a significant step in the part. Therefore, another data-fitting procedure had to be investigated to compensate errors on features that might have critical interface angles to neighboring features. That

is, a least squares technique with prescribed boundary conditions had to be developed. This problem cannot be treated as a standard least squares problem since the boundary conditions restrict the selection of the fitting parameters.

Polynomials are useful as approximation functions to unknown and possibly very complex nonlinear relationships. However, the literature on least squares regression models [25, 26, 27] warns that it is important to keep the order of the polynomial models as low as possible. In an extreme case it is possible to pass a polynomial of order n-1 through n points, so a polynomial of sufficiently high degree can always be found that provides exact interpolation of the data. The behavior of the polynomial between the data points may be highly oscillatory, though, and not provide good data interpolation. Adding intermediate points would actually create a greater likelihood of oscillations between data points, since the order of the polynomial (n-1) must increase with the number of points (n) for the fit to include the points. For the purpose of machining, interpolation between data points is critical, so oscillations are undesirable. Therefore, the number of points per polynomial must be kept low.

When a function behaves differently in different parts of the range of the independent variable the usual approach is to divide the range of the independent variable into segments and fit an appropriate curve in each segment. Spline functions offer a way to perform this type of piecewise polynomial fitting and provide smooth transitions if desired between fitted segments. Splines are generally defined to be low order piecewise polynomials of degree $n$ whose function values and first $n-1$ derivatives agree at the points where they join. The abscissas of these points are called *knots*. Thus a spline is a continuous function with $n-1$ continuous derivatives. Polynomials may be considered a special case of splines with no knots, and piecewise polynomials with fewer than the maximum number of continuity restrictions may also be considered splines [28]. The number and degrees of the polynomial pieces and the number and position of the knots may vary in different situations.

It is possible to construct a *basis*, or sequence of functions, such that every spline of interest can be written in one and only one way as a linear combination of these functions [29]. The cubic splines, with $n = 3$, will be used since they have been shown to be adequate for most practical problems. It was also decided that having a knot at every third compensation point would keep oscillations minimal in the present problem. Cubic splines can be written in terms of basis functions as follows:

Given an ordered sequence of $k$ knots

$$a \le t_1 < t_2 < \ldots < t_k \le b \qquad (1)$$

A cubic spline with these k knots can be written in the form

$$y(x) = \sum_{j=0}^{3} c_j \, x^j + \sum_{j=1}^{k} c_{j+3} (x - t_j)_+^3 \qquad (2)$$

where the $c_j$ are coefficients and

$$(x - t_j)_+^3 = \begin{cases} (x - t_j)^3 & x > t_j \\ 0 & x \le t_j \end{cases} \qquad (3)$$

This cubic spline representation has continuous first and second derivatives. See [25] and [26] for good general discussions of the use of splines in statistical data analysis.

The splines in this application are not unrestricted at their ends, however, and this changes the least squares problem in this case. In order to make the curved features match with neighboring features restrictions must be placed on how the splines behave at the endpoints a and b of the interval. In particular we will require that the splines go through specific points with specific slopes. Therefore we will require the following conditions be satisfied:

$$\begin{aligned} y(a) &= y_0 \\ y(b) &= y_{s+1} \\ \frac{dy}{dx}(a) &= y_0^{(1)} \\ \frac{dy}{dx}(b) &= y_{s+1}^{(1)} \end{aligned} \qquad (4)$$

where $y_0$, $y_{s+1}$, $y_0^{(1)}$, $y_{s+1}^{(1)}$ are prescribed boundary conditions at the end points.

The constrained least squares problem is then to fit equation (2) to the error data subject to the constraints given by equation (4) at the feature boundaries. A full discussion of the algorithm used to solve this problem is given in [30].

The algorithm was coded and integrated with the PIECS software. The application of this algorithm and other routines within PIECS depend on the management of part feature data. For each feature, PIECS has to assess the nominal data and the errors found by on-machine inspection. The appropriate analyses are then performed, and the error compensation instructions computed. Systematic handling of these steps is the key to successful implementation.

## 3.0 Implementation of Process-Intermittent Error Compensation

The major steps for operating the prototype system are as follows. First, rough cut the part and machine it to a semifinished state. Use an NC program to probe the part while it is still on the machine tool. Analyze the semifinished part errors to derive the tool path adjustments for the finish cut. Apply adjusted tool paths during finish machining to compensate anticipated errors. On-machine inspection of the finished part should show minimal process errors.

Software functions collect data during machining and inspection, plot inspection results, and store data in a database. Other than the analysis algorithms, the heart of the software implementation is the systematic way part feature data, both nominal and measured, are provided to routines that perform the error compensation calculations.

### 3.1 Management of Part Feature Data

A database records all data associated with design specifications, machining, inspection procedures, and inspection results for each part to be compensated. The software design for process-intermittent error compensation includes strict means of systematically identifying data (e.g., a probe reading) and linking it to other data (e.g., the corresponding nominal coordinate on a feature). The linking of data is facilitated by a data labeling nomenclature that comprehensively serves the data identification needs of the various software programs. This topic is covered in [31] and [32].

The error compensation strategies require interpreting the part as consisting of separate features. Such decomposition of the part is especially useful for establishing correspondences between design information and manufacturing operations [33]. Dimensional Measuring Interface Specification (DMIS) [34] format is used for formal geometric definitions of part features. Since the database also needs to store certain non-geometric information about each feature, there are two data records for each feature: the DMIS geometric definition and the non-geometric attributes used in these error compensation procedures.

### 3.2 Compensation Calculations for Features with Linear Profiles

If an analysis of the semifinished part errors determines that a constant offset is sufficient to compensate the errors for either axis, then PIECS inserts the appropriate values in the tool offset update command in the NC program segment for the finish cut. In this case, all coordinates in the NC program are left at their nominal values. As an alternative means of compensating the errors, PIECS also writes the axis offsets to a file that may be used for real-time compensation.

Otherwise, PIECS adjusts the tool path for finish machining of each feature. The adjustment for a feature with a nominally linear profile is calculated by fitting a linear function through the compensation points corresponding to the gauge points. This simplified formulation of the compensation curve is usually adequate for linear features (although a spline fit, which is required

for nominally curved features, would also work on linear features). The intersections of the linear equations for consecutive linear features are the compensation points at the ends of the features. These compensation curve intersections are the new "go-to" points for a tool to cut each feature for the finished part. The coordinates of these adjusted points replace the nominal coordinates in the NC program for the finish cut, and are also written to a file that provides data to generate real-time cut adjustments. Elaboration of these procedures may be found [35].

## 3.3 Compensation Calculations for Features with Circular Arc Profiles

Modeling with splines is a technique that can be used in all cases. Simple straight-line fitting may be used instead for most short features with nominally straight profiles because the errors over the length of such a feature seldom vary much. However, because of the likelihood of more significant inflections in the errors on a curved feature, the compensation curves for features with nominally curved profiles need to be fitted with splines. Furthermore, their end points must be constrained according to the adjacent features, as explained earlier. The spline-fitting algorithm coded for the prototype system was restricted to deriving compensation curves only for features with nominally circular (constant-radius) arc profiles. Extending it to apply to a broader range of nominal curves would mainly be a matter of adapting the code to new formats for data representing the equations of the nominal curves.

## 3.4 Producing the Error-Compensated Tool Path

The result of the compensation calculations discussed above is the compensation curve, the adjusted tool path prescribed to compensate errors. The following outline summarizes the steps for determining the error-compensated tool path.

For the semifinished part:

- For each cut containing gauging points:
  - For each gauging point:
    - Determine the *gauged coordinates,* i.e., the coordinates of the position detected by the probe (in the part coordinate frame).
    - Formulate the *gauging point error vector* as originating at the nominal coordinates and terminating at the gauged coordinates.
  - Fit a curve through the gauged coordinates. This *error curve* should be extrapolated so that it will intersect the error curves for the previous and next cuts. (Because of hypothetical cuts defined for calculation purposes, there will always be a cut before and after the current cut.)
- Calculate the *error curve endpoints* as the intersections between the error curves.
- For each error curve endpoint, formulate the *boundary condition error vector,* originating at the nominal point (i.e., the start- or end-point cut coordinates), and terminating at the error curve endpoint. If a cut is along a curved feature, such as an arc, conditions of tangency or non-tangency also have to be specified.

- Reverse the signs of the components of the error vectors to derive the *gauging point compensation vectors* and the *boundary condition compensation vectors*.

For each cut on the finished part:

- Transform the nominal coordinates of the gauging points using the corresponding compensation vectors. The heads of these vectors now locate the *compensation points*.
- Transform the end points of the nominal cut using the boundary condition compensation vectors. The heads of these vectors now locate the *boundary condition coordinates*.
- Fit a curve through the compensation points. Extrapolate the curve so that each end exactly reaches the surface normal vector extended from the end points of the nominal cut. The result is the *compensation curve*.
- Translate, rotate, and scale the compensation curve to make its endpoints coincide with the boundary condition coordinates. The result is the error-compensated tool path.

This logic is in operation in the PIECS software. It was implemented in the prototype system, and proven to be sound, indicated by the results of machining tests.

# 4.0 System Prototype

## 4.1 Hardware

The main hardware components of the prototype process-intermittent error compensation system include the machine tool and its controller, the probe subsystem, a PC computer and a smart interface to the NC controller (Figure 10). The machine tool used in the system is a commercial, 27 kW, turning center. The stylus probe used allows omnidirectional sensing (+/- X, +/- Y, + Z), with a 12.5° over-travel in X and Y directions and 6.5 mm in Z. The stylus trigger force in X and Y is 0.2 N and 2.6 N in Z. The measured repeatability of the probing process on the turning center falls within 0.5 $\mu$m for faces and 1.5 $\mu$m for diameters. This repeatability is the result of a set of 40 repeated probing trials at 15 points on a part with steps. The PC used is connected to the controller by way of a smart interface called The Real-Time Error Corrector (RTEC) [36].

In general, on-machine gauging, using a touch-trigger probe or other probes, can only detect process-induced part errors, not those induced by machine geometric-thermal characteristics. Most geometric errors are reproduced during the probing operation and are not "seen" (i.e., the tool and the measuring probe trace the same incorrect path). Therefore, only process-induced errors, caused by tool dimension, tool wear, tool and/or part deflection, etc., can normally be detected if the probe data are not modified by a geometric-thermal model to compensate errors induced by the machine geometric-thermal characteristics. In that case the errors would include both process and geometric-thermal errors. (There would also be measurement error, e.g. from incorrect stylus size or probe lobing effects. These are not judged to be significant compared to the magnitude of the actual part size errors, and therefore are not included in the discussion.)

The on-machine gauging used in the process-intermittent error compensation is called fast probing. In fast probing, the RTEC captures the axis positions in response to the probe trip and sends them to the PC. At the 2.5 m/min feed rate used, the position must be captured within about 25 $\mu$m to avoid introducing a position error greater than the position resolution of the turning machine used in this study, which is 1 $\mu$m.

Since the RTEC plays an integral part in process-intermittent error compensation, we will briefly describe its features. It was previously described in detail in [36] and [37] and is a generic smart interface that is inserted between the position feedback element of the axes of a machine tool, and the machine-tool controller. The device counts the signals from the feedback element to determine the machine position and sends this position data to a controlling PC computer that records the data. There is a quadrature decoder and microcomputer for each axis. When performing corrections, the RTEC alters the tool path by modifying the square-wave signals for "encoder-type" feedback devices before they go to the machine tool controller (Figure 11). Additional transitions are added which alter the position count in the machine tool controller feedback loop, causing the machine to go to a slightly different position to compensate the predicted errors. The correction counts to be added are determined by the PC computer using a predictive error model.

Although not discussed in this report, thermal sensors would provide data to the model if it were to compensate machine geometric-thermal errors. For the machine tool in use, a two-axis turning center, the position is altered by 2 $\mu$m for each correction count. The relation of RTEC to the machine tool and the PC is shown in Figure 10. A view of a generic internal schema of the RTEC is given in Figure 11.

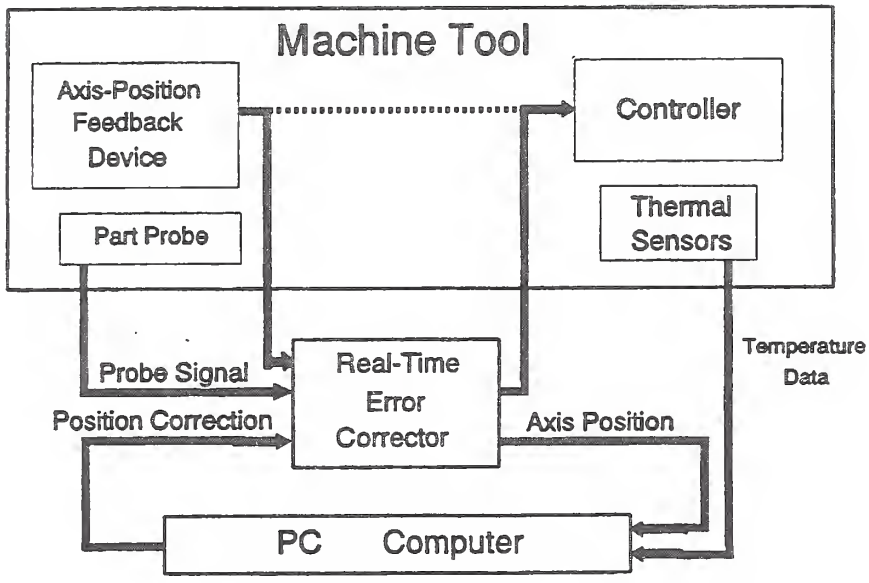



**Figure 10: Error Compensation System**

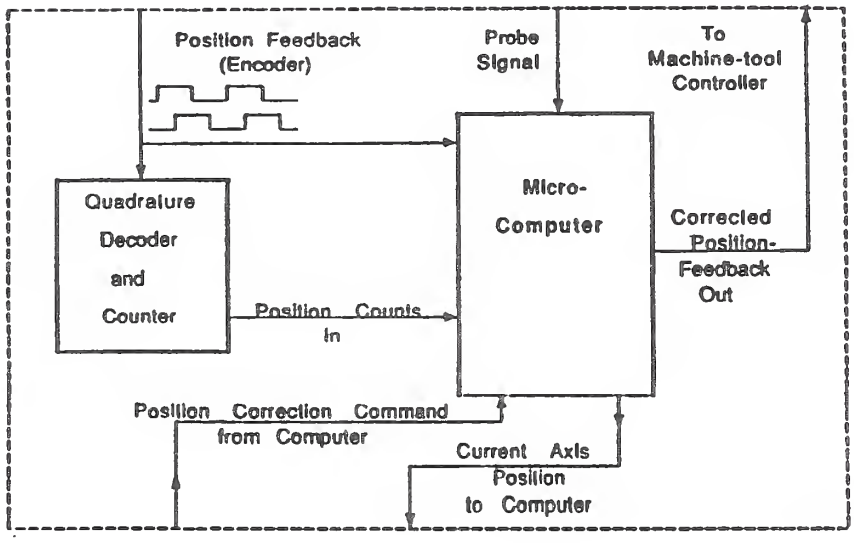



**Figure 11: RTEC Architecture**

The PIECS program itself runs on the PC under the control of a master control program. Although not depicted in Figure 10, the control program also resides on the PC, and sends commands to PIECS, the smart interface, and the NC and probing controllers. The function of PIECS in the overall architecture is to perform off-line analysis of the probed data and prepare input files for the control program to use for tool path compensation during finish machining.

## 4.2. Software Capability

The procedures for producing a part with the prototype process-intermittent error compensation system require specific software capability for data management. Before discussing the data, the basic functionality of software modules will be outlined. There are three major divisions of software functions: pre-process, on-machine (including in-process and process-intermittent), and post-process.

For ease of use, much of the pre-process software consists of CAD-based interactive programs. These software tools are used to define the original part and decompose it into features related to inspection procedures (surface scanning patterns, gauging points and surface normal vectors), machining processes (cuts for each machining session, identifiers of NC code blocks), and error analysis (nominal gauging coordinates, error types). Then interactive procedures use the part design to define the NC paths for dimensional and surface inspection. From the resulting data, NC inspection code is automatically generated. To simplify later steps, the pre-process software may also be used to transfer NC programs to and from the machine tool controller, and to create part description data in the format of the Dimensional Measuring Interface Specification (DMIS). Although not implemented in the prototype, it would also be desirable for software at this stage to facilitate interactive generation of machining programs and DMIS files of post-process inspection instructions.

The on-machine software functions calculate and implement real-time and process-intermittent error compensation; collect data during machining and inspection; plot inspection results; and populate the database. The post-process software functions analyze process-intermittent and post-process inspection data, and calculate adjustments for parameters in error compensation algorithms.

## 4.3. Data Storage and Transfer

The system makes use of data stored in various forms. The commercial software packages used, such as the relational database and the CAD system, store data in their own formats, some of which are binary. Such packages are also capable of writing some data in ASCII form, so that option is used when the data need to be opened in a text editor or read by another program.

In storing and manipulating ASCII data, existing standards were used wherever possible. The machine tool controller requires that the NC programs conform to the ANSI/EIA RS-274 standard. Part feature data are described and stored in DMIS format. Output data to be plotted are written in the comma separated variables (CSV) form that is readable by many commercial data analysis packages. However, most other data are written to files designed to be viewable in a text editor, and to be simply read by the computer programs which manage the error compensation activities. The data are stored in various ASCII formats, as appropriate and convenient.

Data are transferred from one software module to another by various means. Most data accessed by the custom programs are written to files and read from files as stated above. Some data are passed between modules as parameters or external variables. The CAD and database packages have functions to import data from ASCII files. The database also has a C language library, which allows a C program to access the database tables directly.

Data labeling nomenclature has been developed to identify data and relate it to other data. Such information is encoded into part ID numbers, NC program ID numbers, and file names. By interpreting a part ID, one may know the part number, material, and inspection point patterns. For completed parts, the part ID is also used to identify a specific copy among nominally identical parts. The NC program ID denotes the part ID, the stage of the part (rough, semifinished or finished), the pertinent operation (machining, dimensional probing or surface scanning), and if for probing, the direction of the probing.

Many data file names contain the part ID and/or some other of the above information. NC file names contain the entire NC program ID. Detailed descriptions of the data labeling conventions [31] are beyond the scope of this paper, but the concepts as explained suggest the manner of use. The transfer of data requiring special I/O boards (RTEC communications and machine tool temperatures, explained in [38] are also not detailed here; however, the treatment after conversion to values with obvious meaning is described.

## 5.0 Verification Cutting Tests

Three different part designs were used in the testing of PIECS. Each design was used to generate a family of successively smaller parts having the same basic shape. This scheme facilitated repetitive testing by allowing the last part fabricated to be used as the stock for the next part. One part design, FACETST (Figure 12), is made up of only cylinders and faces. Its step-shaped profile consists of straight lines that are parallel to the machine axes during fabrication. In addition to similar cylinders and faces, another design, MODBAS2 (Figure 14), has a tapered cylinder and a hemispherical dome. Therefore its profile includes a non-orthogonal line and an arc. The arc is a half-circle with its ends tangent to the adjacent horizontal straight feature. The third design, PIECS11 (Figure 17), has a tapered cylinder and a spherical knob. In its profile, the circular arc consists of more than half a circle, and the arc's ends meet the adjacent feature at an angle. This design was included because the non-tangent condition imposes different constraints on the PIECS arc algorithm than does the tangent condition. The way PIECS handles different feature configurations was already discussed in Section 2.2. The only intention here is to describe the design, machining and inspection of parts as related to tests conducted to evaluate the various capabilities of PIECS.

The test parts described were designed solely to test the PIECS treatment of various part features and feature configurations, and do not necessarily have any other practical value. The material chosen for all parts is aluminum T6061-T6 because of its machinablity and availability. The turning center used for machining was configured to accept turning stock of diameter 152.4 mm (6 inches). No tailstock was used while machining parts, so the stock length was chosen to be limited to about 254 mm (10 inches). Since all the test parts were designed with unspecified overall lengths, starting with stock this long permits many repetitive experimental cuts to be performed before the final part is removed from the machine tool. By use of parameters, the NC machining programs were written to index the location of the part origin after each execution in a series of experimental cuts, to make the next part shorter.

The process of creating a part design and an NC machining program involves using CAD software to calculate the coordinates to be specified in the NC program. A text-editing program used to generate the NC machining program reads the coordinates. Since only axis-symmetric parts were used, full design information may be conveyed by a drawing of the part's planar profile on one side of the axis of symmetry. The profile of the finished part is drawn full scale as a polyline, a series of connected line and arc segments representing the part features. This polyline represents the nominal path of the cutting tool's point of contact with the part surface. The tool path actually used in the NC machining program is that traversed by the center of the tool nose. Then, the tool path for each cut in a series may be obtained by offsetting the polyline by the sum of the tool nose radius and the thickness of material to remain after the cut. For example, using a tool with a nose radius of 0.7938 mm (0.03125 inches), to machine a part to 0.254 mm (.01 inches) oversize, the NC machining program must specify a tool path that is offset 1.0478 mm (0.04125 inches) from the polyline delineating the nominal part surface. One change made to the CAD-derived data is that all X coordinates had to be doubled, because the turning center is normally programmed in "diameter mode".

Again, the sequence for fabricating a part with process-intermittent error compensation is (1) rough cut, (2) semifinish cut, (3) measure error trend, and (4) finish cut with error compensation. For the experiments, NC rough cut programs for each part were written to leave 0.508 mm (0.02 inches) of extra material on the part. Semifinish cut and NC finish cut programs each removed 0.254 mm (0.01 inches) more, finally leaving each part at its nominal design size (except for errors, of course). For both the semifinish and finish cuts, the feed rate was 0.13 millimeters per revolution, and the spindle speed was 2400 revolution per minute. Each tool used to cut each part was an 80° diamond-shaped uncoated carbide insert in a 15° positive rake toolholder. Probing is done without any error compensation in effect, so only process errors are measured (within the repeatability stated in Section 4.1).

## 5.1 A Part with Only Orthogonal Linear Features (FACETST)

The first series of experiments was designed to test the effectiveness of PIECS in correcting simulated process errors on a turned part having a profile made up of only orthogonal linear features. The part designed for this purpose, FACETST, is shown in Figure 12, where A = 14.986 cm and B = 5.080 cm.

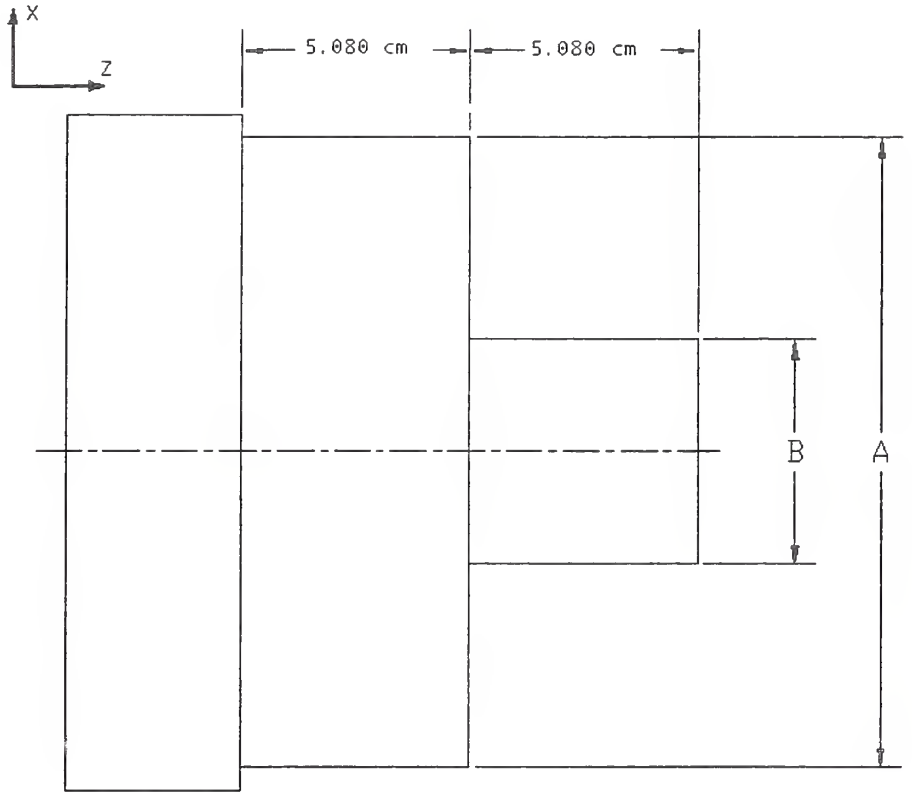



**Figure 12: FACETST Part with Linear Features**

This part is the first in a family of parts with successively smaller dimensions A and B. The small depth of cut used for semifinish and finish machining causes minimal tool deflection or other process-induced errors. Therefore, tool path deviations were introduced to simulate significant process errors that could be compensated. Small offsets were made to the locations of the end points of the cuts for each feature in the semifinish and finish cut NC machining programs. These adjustments were "unknown" to PIECS, which compares part measurements to the nominal specifications from the CAD drawing. The simulated errors appeared as slight tapers in the straight-line feature profiles. Deviations of about 12 $\mu$m were added to the end points of each turning cut; and deviations of about 25 $\mu$m to the end points of each facing cut. The slopes of the "errors" had opposite signs for the two turning cuts and two facing cuts. The errors at the probing points are calculated as the differences between the nominal coordinates and the measured coordinates. The errors at each of the 15 probing locations on FACETST, measured after the semifinish cut and the compensated finish cut, are shown in Table 1. The complete profile of a feature is assumed to be represented by a curve fitted through the measured points and extrapolated to the ends of the feature. Figure 12 shows a picture of FACETST as it appears after the finish turning operation. Figure 13 shows the locations of the gauging points, depicting only the portion of the part above the axis of symmetry, shown secured in the turning center chuck.

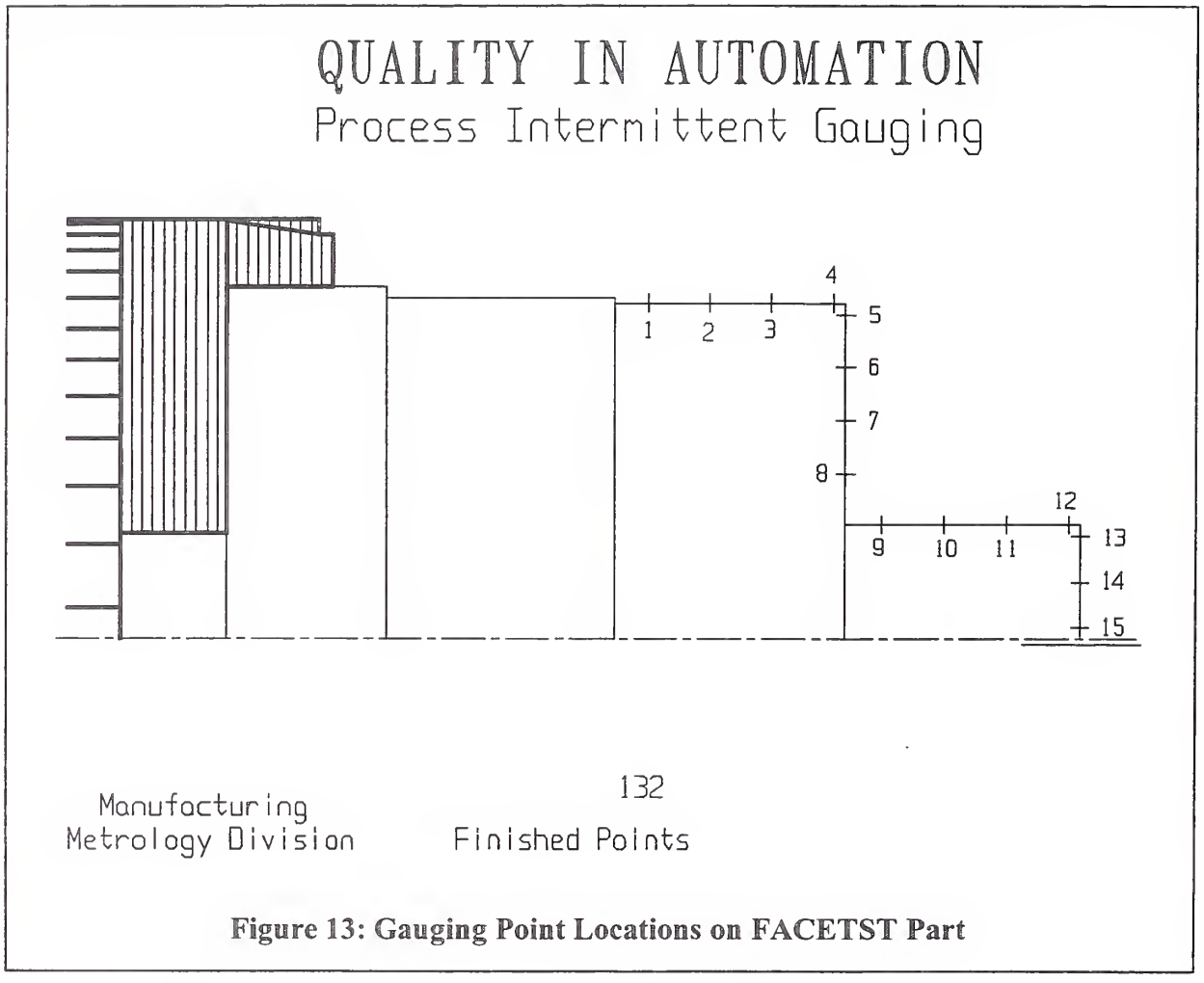



**Figure 13: Gauging Point Locations on FACETST Part**

| Point Number | Semifinish Cut Error ($\mu$m) | Finish Cut Error ($\mu$m) |
|---|---|---|
| 1 | 3 | -2 |
| 2 | 6 | 0 |
| 3 | 9 | 0 |
| 4 | 13 | -2 |
| 5 | 8 | 4 |
| 6 | 14 | 5 |
| 7 | 17 | 3 |
| 8 | 25 | 4 |
| 9 | -4 | -4 |
| 10 | -8 | -4 |
| 11 | -11 | -3 |
| 12 | -17 | -2 |
| 13 | 0 | 0 |
| 14 | -9 | 0 |
| 15 | -17 | 0 |

**Table 1: Typical Results Showing Differences in Probing Between Semifinished and Finished Parts**

For determining the Z coordinates of points probed, a reference point is selected and assumed to have a known Z coordinate. The machine Z coordinate reported by the RTEC when this point is probed is subtracted from the known part Z coordinate, resulting in the offset of the part coordinate system from the machine coordinate system. For tests on FACETST, point 3 is the chosen Z reference point, and therefore the errors are zero for both cuts (semifinish and finish) at this location. As can be seen from the data in Table 1, the errors on the front face (points 13-15) that were as high as 17 $\mu$m in the semifinish cut are completely compensated.

For the smaller diameter cylinder (points 9-12), the taper, which had a magnitude of 13 $\mu$m over the range of the probing points, was reduced to 2 $\mu$m. However, a small error of about -3 $\mu$m in radius remains. On the "upper" face (points 5-8), the taper was effectively removed, but a size error of about +4 $\mu$m remains. The larger diameter cylinder was compensated well for both taper and size.

Considering that the purpose of the experimental analyses is to compare measurement data sets taken under very similar conditions before and after compensation, the uncertainties associated with thermal changes and machine tool related systematic effects were not considered part of the uncertainty estimation. Thus, the standard uncertainty of measurements was determined by a Type B evaluation [39], using the probing repeatability information stated in Section 4.1. Assuming a uniform distribution, the standard uncertainty, $u_{dia}$, of the diameter measurements was calculated as

$$u_{dia} = \sqrt{\frac{R^2_{dia}}{12}} = 0.43\ \mu m$$

where $R_{dia}$ is the range of variation in measurements of diameters. The standard uncertainty, $u_{face}$, of face measurements was calculated as

$$u_{face} = \sqrt{\frac{R^2_{face}}{12}} = .14\ \mu m$$

where $R_{face}$ is the range of variation in measurements of faces. Therefore, the expanded uncertainty ($k = 2$) for fast probing on this machine is 0.3 $\mu$m for measuring faces and 0.9 $\mu$m for measuring diameters. The largest residual error was 5 $\mu$m at point 6. It is possible that 0.3 $\mu$m of this is probing uncertainty. Since a dimensional error is defined here to be a size deviation normal to the feature surface, the error parallel to the surface is usually nearly zero. So, in the case of part surfaces that are parallel to the machine axes, error may be significant in one axis direction, and not in the other.

Each part in the following data tables is identified by a four-digit part number and a three-digit extension. The finished stage of a part has the same part number as the semifinished stage, but the extension of the finished stage is one greater than the extension for the semifinished stage. With this knowledge, the semifinished and finished stages of the same part may be compared. Note that the mean error would often be greater than shown if calculated with the errors' absolute values.

| X-Error, Semifinished Linear-Feature Part ($\mu$m) | | | | | |
|---|---|---|---|---|---|
| Point # | Part #1411.559 | Part #1411.606 | Part #1511.561 | Part #1511.608 | Mean |
| 1 | 3 | -7 | -4 | -11 | -5 |
| 2 | 6 | -7 | -13 | -5 | -5 |
| 3 | 9 | 1 | -25 | -3 | -5 |
| 4 | 13 | 2 | -35 | 0 | -5 |
| 5 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 |
| 9 | -4 | -14 | -1 | -16 | -9 |
| 10 | -8 | -17 | 11 | -20 | -9 |
| 11 | -11 | -22 | 20 | -24 | -9 |
| 12 | -17 | -24 | 31 | -26 | -9 |
| 13 | 0 | 0 | 0 | 0 | 0 |
| 14 | 0 | 0 | 0 | 0 | 0 |
| 15 | 0 | 0 | 0 | 0 | 0 |

**Table 2: X- Errors for Four Semifinished Linear-Feature Parts (FACETST Family)**

Having nominally straight-line profiles parallel to the machine axes, these features essentially test error compensation for the X and Z axes separately. To compare how effectively compensation is applied for each machine axis, data tables for the FACETST parts are shown for the X error, Z error and total (combined X and Z) error for both the semifinished and finished stages of each part. (Only the total error is shown for the other parts.) Tables 2 through 4 give the X, Z and combined semifinish errors on four parts (denoted here by the four-digit part ID number followed by an extension number indicating the inspection data set: 1411.559, 1411.606, 1511.561 and 1511.608) in the FACETST family of parts. The values are shown in micrometers. The taper errors deliberately produced on the linear features, as explained before, are clearly shown in Tables 2 and 3. Because of the artificial errors, the error on one feature of a semifinished part should not be compared to the error on the same feature of another semifinished part. Even within the same family of parts, the artificial errors added to features were somewhat arbitrary. Therefore, the mean of the semifinish errors is not useful except to compare to the mean of finish errors to determine mean error reduction.

Tables 5 through 7 show the results of PIECS compensation during finish cut machining of the same four parts (parts 1411.560, 1411.607, 1511.562 and 1511.609). (Note that the inspection data set extension is incremented by one for each part, indicating that inspection of the finished part was the next inspection after that of the semifinished part.) In general, PIECS reduced the significant errors measured on the semifinished part to less than 5 $\mu$m of residual error on the finished part. Variations in finished part errors are interesting because those are errors remaining after an attempt to reduce them to zero. For this reason, the standard deviation of the errors is added to the tables for the finished parts.

| Z-Error, Semifinished Linear-Feature Part ($\mu$m) | | | | | |
|---|---|---|---|---|---|
| Point # | Part #1411.559 | Part #1411.606 | Part #1511.561 | Part #1511.608 | Mean |
| 1 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 |
| 5 | 8 | -1 | 5 | 2 | 3 |
| 6 | 14 | 9 | 12 | 9 | 11 |
| 7 | 17 | 12 | 19 | 14 | 15 |
| 8 | 25 | 18 | 22 | 19 | 21 |
| 9 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 |
| 11 | 0 | 0 | 0 | 0 | 0 |
| 12 | 0 | 0 | 0 | 0 | 0 |
| 13 | 0 | 0 | 0 | 0 | 0 |
| 14 | -9 | 18 | -9 | 17 | 4 |
| 15 | -17 | 35 | -20 | 34 | 8 |

**Table 3: Z-Errors for Four Semifinished Linear-Feature Parts (FACETST Family)**

| Combined Error, Semifinished Linear-Feature Part ($\mu$m) | | | | | |
|---|---|---|---|---|---|
| Point # | Part #1411.559 | Part #1411.606 | Part #1511.561 | Part #1511.608 | Mean |
| 1 | 3 | -7 | -4 | -11 | -5 |
| 2 | 6 | -7 | -13 | -5 | -5 |
| 3 | 9 | 1 | -25 | -3 | -5 |
| 4 | 13 | 2 | -35 | 0 | -5 |
| 5 | 8 | -1 | 5 | 2 | 3 |
| 6 | 14 | 9 | 12 | 9 | 11 |
| 7 | 17 | 12 | 19 | 14 | 15 |
| 8 | 25 | 18 | 22 | 19 | 21 |
| 9 | -4 | -14 | -1 | -16 | -9 |
| 10 | -8 | -17 | 11 | -20 | -9 |
| 11 | -11 | -22 | 20 | -24 | -9 |
| 12 | -17 | -24 | 31 | -26 | -9 |
| 13 | 0 | 0 | 0 | 0 | 0 |
| 14 | -9 | 18 | -9 | 17 | 4 |
| 15 | -17 | 35 | -20 | 34 | 8 |

**Table 4: Combined Errors for Four Semifinished Linear-Feature Parts (FACETST Family)**

| X-Error, Finished Linear-Feature Part ($\mu$m) | | | | | | |
|---|---|---|---|---|---|---|
| Point # | Part #1411.560 | Part #1411.607 | Part #1511.562 | Part #1511.609 | Mean | Std. Dev. |
| 1 | -2 | -3 | -3 | 0 | -2 | 1 |
| 2 | 0 | -2 | -1 | 2 | 0 | 2 |
| 3 | 0 | -2 | -5 | -3 | -3 | 2 |
| 4 | -2 | 0 | 0 | 0 | -1 | 1 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | -4 | 2 | -3 | -2 | -2 | 3 |
| 10 | -4 | 4 | -1 | -3 | -1 | 4 |
| 11 | -3 | 5 | -1 | 1 | 1 | 3 |
| 12 | -2 | 3 | -3 | -1 | -1 | 3 |
| 13 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table 5: X-Errors for Four Finished Linear-Feature Parts (FACETST Family)**

| Z-Error, Finished Linear-Feature Part ($\mu$m) | | | | | | |
|---|---|---|---|---|---|---|
| Point # | Part #1411.560 | Part #1411.607 | Part #1511.562 | Part #1511.609 | Mean | Std. Dev. |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 4 | 5 | -5 | -1 | 1 | 5 |
| 6 | 5 | 3 | -2 | -2 | 1 | 4 |
| 7 | 3 | 4 | -1 | -3 | 1 | 3 |
| 8 | 4 | 3 | -3 | -2 | 1 | 4 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 0 | -1 | -1 | 2 | 0 | 1 |
| 15 | 0 | -1 | 0 | 1 | 0 | 1 |

**Table 6: Z-Errors for Four Finished Linear-Feature Parts (FACETST Family)**

| Combined Error, Finished Linear-Feature Part ($\mu$m) | | | | | | |
|---|---|---|---|---|---|---|
| Point # | Part #1411.560 | Part #1411.607 | Part #1511.562 | Part #1511.609 | Mean | Std. Dev. |
| 1 | -2 | -3 | -3 | 0 | -2 | 1 |
| 2 | 0 | -2 | -1 | 2 | 0 | 2 |
| 3 | 0 | -2 | -5 | -3 | -3 | 2 |
| 4 | -2 | 0 | 0 | 0 | -1 | 1 |
| 5 | 4 | 5 | -5 | -1 | 1 | 5 |
| 6 | 5 | 3 | -2 | -2 | 1 | 4 |
| 7 | 3 | 4 | -1 | -3 | 1 | 3 |
| 8 | 4 | 3 | -3 | -2 | 1 | 4 |
| 9 | -4 | 2 | -3 | -2 | -2 | 3 |
| 10 | -4 | 4 | -1 | -3 | -1 | 4 |
| 11 | -3 | 5 | -1 | 1 | 1 | 3 |
| 12 | -2 | 3 | -3 | -1 | -1 | 3 |
| 13 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 0 | -1 | -1 | 2 | 0 | 1 |
| 15 | 0 | -1 | 0 | 1 | 0 | 1 |

**Table 7: Combined Errors for Four Finished Linear-Feature Parts (FACETST Family)**

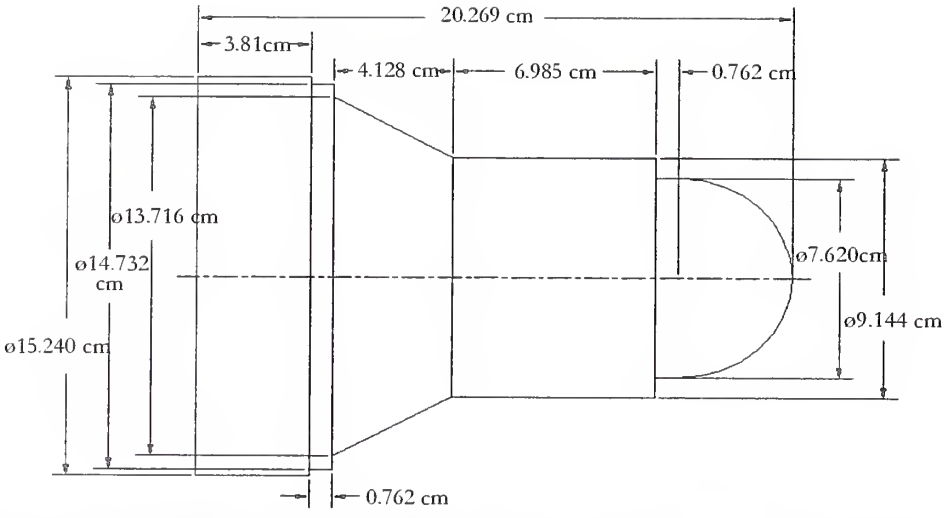



**Figure 14: MODBAS2 Part with Cylinder, Taper and Dome Features.**

## 5.2 A Part with a Curved Feature Requiring Tangency at End (MODBAS2)

The main features of this part, MODBAS2 (Figure 14), are a step portion on the largest diameter area, a small vertical face, a long taper, a cylinder, and a hemisphere. PIECS compensates errors on all of these surfaces. This part was particularly useful to test how well errors on the hemisphere could be compensated using the spline algorithm described in [30]. The objective was to verify that the algorithm adequately models the errors on an arc profile which is tangent to a linear profile. For some parts in the MODBAS2 family, a mock error was created on the taper feature in the same manner as for FACETST. Otherwise, all the errors encountered were produced without any deliberate tampering with the specified tool path. However, the cutting tool was randomly selected from a batch known to be significantly worn. The exact nature of the wear was unknown at the time of selection. It was thought that this would be a good test of the algorithm, since the errors generated at the semifinish cut would be unknown beforehand to the operator. The resulting semifinished part showed errors that indicated the worn spot was centered at about the 45° angle on the tool tip. This can be seen in Figure 15. The errors are shown as scaled bars that are called "whiskers". These errors are reflected in the probed errors reported in Table 8 for four parts in the MODBAS2 family. The numbers in the "Point #" column in Table 8 are the gauging points in Figure 15. They are numbered from left to right: points 1-5 on the cone, 6-10 on the large cylinder wall, 11 on the large cylinder face (not visible in the Figure), 12 on the small cylinder wall, and 13-32 on the dome. The errors in the table are in micrometers.

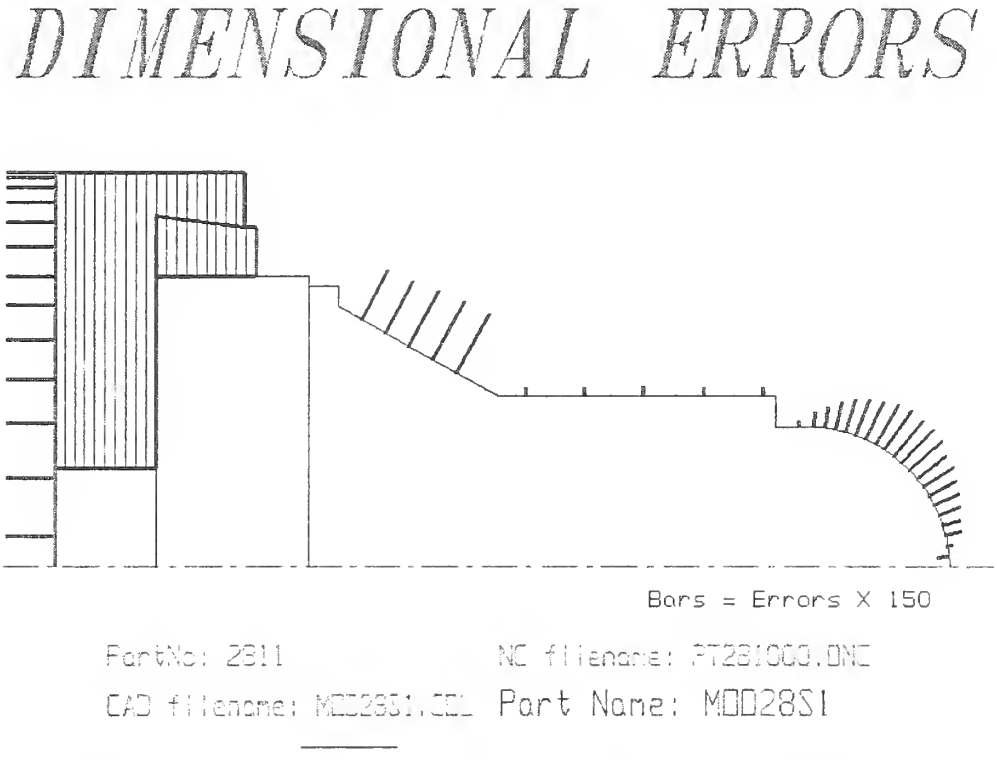



**Figure 15: A "whiskers" plot of the Errors on the Semi-Finish Part**

| Combined Error, Semifinished Tangent-Curve Part ($\mu$m) | | | | | |
|---|---|---|---|---|---|
| Point # | Part #2511.139 | Part #2611.141 | Part #2711.143 | Part #2811.145 | Mean |
| 1 | 86 | 88 | 92 | 95 | 90 |
| 2 | 88 | 90 | 92 | 101 | 93 |
| 3 | 87 | 88 | 90 | 107 | 93 |
| 4 | 88 | 86 | 90 | 114 | 94 |
| 5 | 85 | 83 | 87 | 115 | 93 |
| 6 | 10 | 10 | 15 | 15 | 12 |
| 7 | 8 | 8 | 15 | 14 | 11 |
| 8 | 8 | 7 | 13 | 16 | 11 |
| 9 | 9 | 10 | 14 | 14 | 12 |
| 10 | 10 | 11 | 15 | 14 | 12 |
| 11 | 0 | 0 | 0 | 0 | 0 |
| 12 | 7 | 3 | 9 | 8 | 7 |
| 13 | 21 | 20 | 23 | 23 | 22 |
| 14 | 29 | 30 | 34 | 33 | 32 |
| 15 | 42 | 43 | 46 | 47 | 45 |
| 16 | 50 | 49 | 56 | 56 | 53 |
| 17 | 61 | 63 | 63 | 65 | 63 |
| 18 | 70 | 68 | 71 | 70 | 70 |
| 19 | 72 | 75 | 81 | 77 | 76 |
| 20 | 75 | 77 | 82 | 80 | 78 |
| 21 | 75 | 78 | 78 | 78 | 77 |
| 22 | 74 | 79 | 77 | 77 | 77 |
| 23 | 69 | 68 | 73 | 74 | 71 |
| 24 | 61 | 65 | 66 | 62 | 64 |
| 25 | 57 | 58 | 59 | 61 | 59 |
| 26 | 46 | 53 | 54 | 53 | 51 |
| 27 | 43 | 45 | 46 | 47 | 45 |
| 28 | 34 | 40 | 35 | 38 | 37 |
| 29 | 29 | 35 | 35 | 33 | 33 |
| 30 | 22 | 28 | 30 | 30 | 27 |
| 31 | 3 | 10 | 9 | 10 | 8 |
| 32 | -23 | -17 | -18 | -17 | -19 |

**Table 8: Combined Errors for Four Semifinished Tangent-Curve Parts (MODBAS2 Family)**

Table 9 lists the residual errors on four parts in the MODBAS2 family after PIECS compensation. With the exception of a few outliers the residual errors fall again within 5 $\mu$m or better. This is shown graphically in Figure 16.

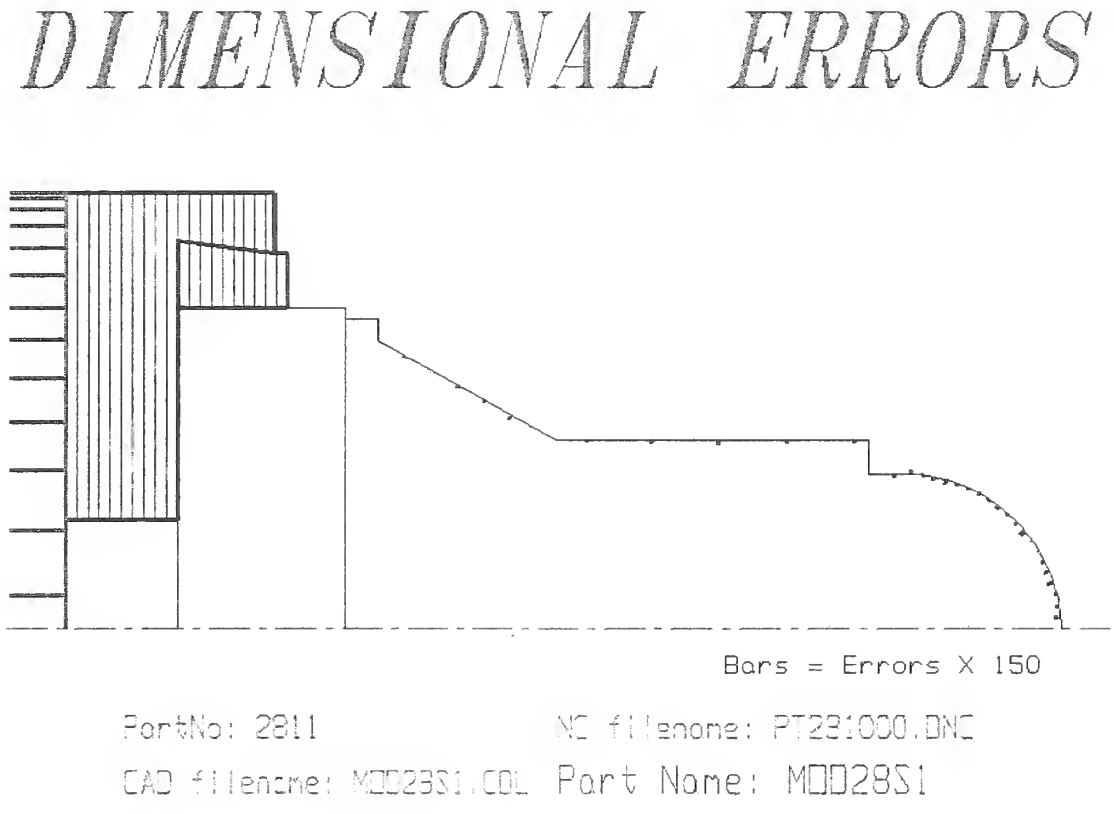



**Figure 16: "Whiskers" Plot of the Reduced Errors on the Finished Part**

| Combined Error, Finished Tangent-Curve Part ($\mu$m) | | | | | | |
|---|---|---|---|---|---|---|
| Point # | Part # 2511.140 | Part #2611.142 | Part #2711.144 | Part #2811.146 | Mean | Std. Dev. |
| 1 | 0 | -1 | -2 | 1 | -1 | 2 |
| 2 | 2 | -2 | -3 | 0 | -1 | 2 |
| 3 | -1 | -1 | -4 | -1 | -2 | 1 |
| 4 | -2 | -2 | 0 | 1 | -1 | 1 |
| 5 | -7 | -1 | 0 | -5 | -3 | 3 |
| 6 | -1 | 1 | 0 | -1 | 0 | 1 |
| 7 | -1 | 3 | -1 | -3 | -1 | 3 |
| 8 | -2 | -1 | -2 | -5 | -3 | 2 |
| 9 | -5 | -1 | -2 | -4 | -3 | 2 |
| 10 | -5 | 0 | -1 | -3 | -2 | 2 |
| 11 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | -5 | -3 | -1 | -4 | -3 | 2 |
| 13 | 6 | 9 | 11 | 6 | 8 | 2 |
| 14 | 4 | 5 | 4 | 1 | 3 | 2 |
| 15 | -2 | -1 | -1 | -4 | -2 | 1 |
| 16 | -2 | -7 | -4 | -6 | -5 | 2 |
| 17 | -3 | -5 | 0 | -2 | -3 | 2 |
| 18 | 3 | -1 | 0 | 2 | 1 | 1 |
| 19 | 1 | 3 | -1 | 4 | 2 | 2 |
| 20 | -2 | -1 | -2 | 2 | -1 | 2 |
| 21 | 1 | -4 | -8 | -3 | -3 | 4 |
| 22 | 3 | -4 | -6 | 2 | -1 | 4 |
| 23 | -3 | -7 | -3 | -1 | -3 | 3 |
| 24 | -2 | 0 | -6 | -5 | -3 | 3 |
| 25 | 1 | -2 | -4 | -1 | -2 | 2 |
| 26 | -3 | -2 | -3 | 2 | -2 | 2 |
| 27 | -1 | -8 | -4 | -1 | -3 | 3 |
| 28 | -1 | -7 | -12 | -4 | -6 | 5 |
| 29 | -4 | -7 | -7 | -7 | -6 | 2 |
| 30 | 6 | -1 | -2 | 3 | 2 | 4 |
| 31 | 4 | -4 | -5 | 2 | -1 | 4 |
| 32 | -6 | -10 | -13 | -5 | -9 | 4 |

**Table 9: Combined Errors for Four Finished Tangent-Curve Parts (MODBAS2 Family)**

## 5.3 A Part with a Curved Feature Requiring Non-Tangency at End (PIECS11)

The same tool used to cut MODBAS2 was used to cut PIECS11. Thus, the errors produced on the tapered cone and spherical feature were similar to those produced on the semifinished MODBAS2 part. The most significant difference from MODBAS2 is that the spherical feature in PIECS11 is not tangent to the adjacent feature. This configuration was included to test how well the spline procedures could model non-tangent end conditions. Another difference is that the spherical feature on PIECS11 is more of a knob than a hemisphere, exceeding the 180° limit of the dome on MODBAS2. This condition tested the spline boundary conditions even more rigorously. The results of the spline modeling and error compensation for PIECS11 were very similar to those obtained for MODBAS2, as shown below.

The part is shown in Figure 17. The numbers in the "Point #" columns in Tables 10 and 11 are the gauging points on the PIECS11 part, equally spaced on each feature. The points are numbered from the large diameter end to near the end of the dome: point 1 on the face of the largest cylinder, 2 on the wall of the next cylinder, 3-6 on the cone, and 7-26 on the dome.

The semifinished part errors are shown in Table 10. The errors remaining after finish machining with compensation are in Table 11.

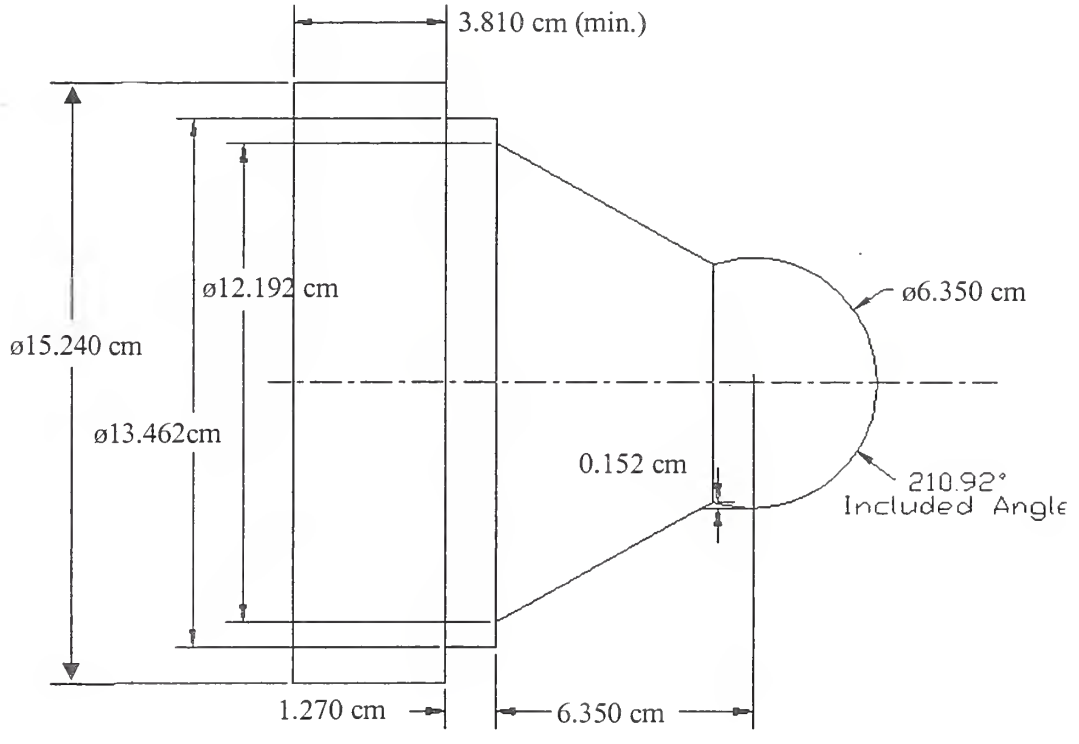



**Figure 17: PIECS11 Part with Non-Tangent Taper and Dome**

| Combined Error, Semifinished Non-Tangent-Curve Part (μm) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Point # | Part #3511.158 | Part #3611.160 | Part #3711.162 | Part #3811.154 | Part #3812.165 | Part #3911.167 | Mean |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | -4 | -4 | 1 | -2 | -6 | -3 |
| 3 | 72 | 69 | 66 | 72 | 66 | 62 | 68 |
| 4 | 69 | 63 | 62 | 72 | 66 | 60 | 65 |
| 5 | 67 | 60 | 57 | 68 | 62 | 56 | 62 |
| 6 | 64 | 57 | 55 | 66 | 56 | 51 | 58 |
| 7 | -67 | -72 | -74 | -75 | -77 | -81 | -74 |
| 8 | -45 | -45 | -52 | -49 | -52 | -55 | -50 |
| 9 | -21 | -20 | -23 | -26 | -25 | -29 | -24 |
| 10 | 2 | -1 | -5 | -6 | -5 | -9 | -4 |
| 11 | 16 | 10 | 6 | 6 | 8 | 4 | 8 |
| 12 | 28 | 22 | 19 | 21 | 20 | 16 | 21 |
| 13 | 39 | 34 | 28 | 33 | 31 | 26 | 32 |
| 14 | 49 | 43 | 42 | 46 | 39 | 38 | 43 |
| 15 | 57 | 48 | 44 | 57 | 47 | 42 | 49 |
| 16 | 57 | 52 | 50 | 56 | 53 | 45 | 52 |
| 17 | 54 | 53 | 49 | 58 | 52 | 46 | 52 |
| 18 | 56 | 51 | 46 | 53 | 47 | 45 | 50 |
| 19 | 49 | 44 | 41 | 44 | 42 | 39 | 43 |
| 20 | 41 | 38 | 33 | 38 | 35 | 33 | 36 |
| 21 | 37 | 33 | 25 | 28 | 25 | 22 | 28 |
| 22 | 29 | 25 | 20 | 25 | 21 | 18 | 23 |
| 23 | 25 | 19 | 14 | 18 | 14 | 13 | 17 |
| 24 | 16 | 12 | 11 | 12 | 12 | 8 | 12 |
| 25 | 0 | -7 | -4 | 1 | -5 | -5 | -3 |
| 26 | -30 | -32 | -33 | -28 | -34 | -33 | -32 |

**Table 10: Combined Errors for Six Semifinished Non-Tangent-Curve Parts (PIECS11 Family)**

| Combined Error, Finished Non-Tangent-Curve Part ($\mu$m) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Point # | Part #3511.159 | Part #3611.161 | Part #3711.164 | Part #3811.155 | Part #3812.166 | Part #3911.169 | Mean | Std. Dev. |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | -2 | 3 | 3 | -2 | -3 | -1 | 0 | 3 |
| 3 | -5 | 1 | 0 | -2 | 1 | -2 | -1 | 2 |
| 4 | -5 | -1 | -1 | -3 | 1 | -2 | -2 | 2 |
| 5 | -3 | 3 | -2 | -2 | -2 | 1 | -1 | 2 |
| 6 | -5 | 1 | -3 | -7 | -2 | -4 | -3 | 3 |
| 7 | -6 | -7 | -9 | -3 | -7 | -7 | -7 | 2 |
| 8 | 3 | 2 | -2 | 5 | 4 | 3 | 2 | 2 |
| 9 | 1 | 4 | -3 | 4 | -1 | 1 | 1 | 3 |
| 10 | -3 | 1 | -5 | 5 | 0 | -2 | -1 | 3 |
| 11 | -3 | -4 | -7 | 0 | -6 | -6 | -4 | 3 |
| 12 | -6 | -3 | -5 | 2 | -1 | -3 | -2 | 3 |
| 13 | -4 | 1 | -4 | -1 | -3 | -3 | -2 | 2 |
| 14 | -6 | 1 | -2 | -2 | -2 | 1 | -2 | 2 |
| 15 | -9 | -1 | -4 | -4 | -2 | -4 | -4 | 3 |
| 16 | -9 | -2 | -7 | -6 | -3 | -4 | -5 | 3 |
| 17 | -10 | -5 | -5 | -10 | -6 | -6 | -7 | 2 |
| 18 | -6 | -2 | -6 | -8 | -6 | -9 | -6 | 3 |
| 19 | -7 | -3 | -2 | -3 | -2 | -3 | -3 | 2 |
| 20 | -5 | -6 | -4 | -1 | -1 | -2 | -3 | 2 |
| 21 | -5 | -6 | -3 | -6 | -3 | -5 | -5 | 1 |
| 22 | -7 | -4 | -4 | -7 | -1 | -6 | -5 | 2 |
| 23 | -8 | -6 | -5 | -8 | -7 | -8 | -7 | 1 |
| 24 | -4 | -1 | 1 | -6 | -2 | -5 | -3 | 2 |
| 25 | -1 | 3 | 5 | 2 | 2 | 2 | 2 | 2 |
| 26 | -8 | -9 | -5 | -12 | -9 | -10 | -9 | 2 |

**Table 11: Combined Errors for Six Finished Non-Tangent-Curve Parts (PIECS11 Family)**

## 6.0 Conclusions

The described implementation of PIECS was shown to produce very significant reductions in process errors. For all tests, the semifinished and finished stages of each part were compared to see the reduction of error due to the error compensation process. As the tables of part data show, compensation greatly diminished the errors in every case.

Since each feature of the FACETST part has a nominal profile parallel to one of the machine axes, errors on a feature are significant in only one axis direction, and negligible in the other. On the finished part, the mean residual errors for points with only X errors were found to be within 2 $\mu$m of those with only Z errors, within the RTEC control resolution of 2 $\mu$m. (See Section 4.1.) The effectiveness of error compensation was not significantly different for the two axes.

The most dramatic error reduction was seen with the artificially-created errors on the finished FACETST parts. The Z error tapers on the semifinished parts ranged as high as 25 $\mu$m. The greatest residual Z error on the finished part after compensation had a magnitude of 5 $\mu$m. Similarly, the X taper errors were reduced from as high as 35 $\mu$m to a maximum of 5 $\mu$m. The average of all the mean residual errors on the FACETST parts is less than one $\mu$m.

An objective of the tests with the MODBAS2 parts was to maintain tangency in the feature profile between the arc and contiguous line. The mean error at the end of the arc was reduced from 22 $\mu$m to 8 $\mu$m, while the mean error at the start of the line was reduced from 7 $\mu$m to -3 $\mu$m. So, the discontinuity at the junction between the features was reduced from 15 $\mu$m to 11 $\mu$m. For the PIECS11 parts, there is no slope condition to be met at the end of the arc. Yet, for both part families, the magnitudes of the residual errors on the arc increase slightly as the next feature is approached. While the algorithm achieves its goal of improving continuity where necessary at the junction between features, future refinements will strive for better continuity.

Although this report covers only limited experiments conducted on a two-axis prototype system, the potential exhibited validates the effectiveness of the methodology. The success of the prototype does suggest several directions in which applications of the methodology may be extended.

First of all, it is expected that errors can be reduced on more types of part features than demonstrated here. Earlier reports showed the practical application of process-intermittent error compensation on two-dimensional features with linear profiles. This report presents the results of experiments that use spline fitting to compensate errors on circular arcs. Splines fitting may be adapted to fit errors on profiles with arbitrary curvature, thus accommodating a wide range of two-dimensional feature types.

Secondly, the error compensation techniques should be effective on parts with many different arrangements of features with different end point constraints. By applying

boundary conditions to the spline fits, tangency at the junctions between features was maintained where required of parts discussed here. In a similar way, any angular relationship between features could be preserved as a finished part is being machined with reduced process errors. This capability can allow a great deal of variability in the axis-symmetric part designs, which qualify, for fabrication using process-intermittent error compensation.

A third extension of a process error compensation system would be from the two-axis machining discussed here to machining with three or more axes. The principles underlying process-intermittent error compensation are presented in this report in terms of two-dimensional examples. However, the principles themselves are not restricted to two dimensions, even though the specific methods for these experiments were developed to apply only to two dimensional part profiles. Adapting the methodology to three-dimensional part errors would involve fitting with three-dimensional splines over surface patches rather than two-dimensional splines. The development of algorithms and methods for three dimensions would be significantly more complex since more surface patch boundary conditions have to be satisfied, but the principles and steps would be similar.

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# APPENDIX

## A. NC Part Programs for Test Part Machining

The NC part programs for machining were developed for the Monarch Metalist turning center in conformance with the requirements of the Mark Century GE2000T CNC controller. References used are the *Mark Century GE2000T Part Programming Manual(May 1984),* and the *Monarch Sidney Programming & Operator's Manual for the Metalist with GE2000T Control (June 1985).*

### A.1. Important Commands for Rough Cutting

Rough cutting of the parts included the use of two especially important NC commands: the G02 command for circular interpolation, and the G81 command for the turning canned cycle. A brief description of these commands is included here to better understand the NC programs listed in this report.

In general, each of these commands is preceded by an M57 word. This option makes sure that the spindle is within ±10% of the programmed speed before continuing cutting. The roughing program uses constant surface speed, and this pause gives the spindle time to change speed to suit the next pass of the cutting tool as the radius changes.

#### A.1.1. The G02 Clockwise Circular Interpolation Mode for Arc Programming

Normally, arcs cut on the Monarch Metalist are of a single-quadrant type, and can be programmed with the radius of the arc. When a multi-quadrant arc is desired, signed arc center offsets must be used. A machine setup data (MSD) parameter must be changed in order to cut multi-quadrant arcs. The system parameter is BLN0012 and should be set to "true." This sets the arc center offsets to be signed. The default setting for this parameter is "false," or non-signed arc center offsets. This parameter can only be changed by password access.

The G02 command requires that the tool be initially positioned at the start point of the arc. The routine will then cut to the end of the defined arc. The G02 command is a sequence of numerical control "words" delimited by spaces, each word consisting of an alphabetic character immediately followed by a numeric value. The form of the G02 command is

N_____ G02 X_____ Z_____ I_____ K_____ F_____

where the blanks represent the numeric values that correspond to the preceding character.

N value is the block label, a number identifying a line in the NC program
G02 indicates cutting a clockwise arc (G03 cuts a counterclockwise arc)
X and Z values are the coordinates of the endpoints of the arc to be cut

I and K values are signed offsets from the start point of the arc
F value is the programmed feed rate along the tool path

### A.1.2. The G81 Longitudinal Turning Canned Cycle

A canned cycle is a single-block command that initiates a routine of multiple tool movements. The G81 canned cycle is used to rough out either internal or external longitudinal turning operations. In our case, we are using it for external roughing. This cycle only needs a few coordinates and parameters set for it to calculate the required number of passes and the shape of the rough-out area. It is necessary that the tool be initially positioned at the start point of the operation. The cycle will return the tool to the start point after completing the cuts.

The form of the G81 command as used in the rough cut program is

N_____ G81 X_____Y_____ F_____P1=_____P2=_____

where

N value is the block label, a number identifying a line in the NC program
X value is the absolute coordinate of the final depth for the tool to traverse
Z value is the absolute coordinate of the final length where the tool exits the rough-out zone
F value is the programmed feed rate
P1 value is the maximum programmed depth-of-cut per pass
P2 value is the Z value at start of the exit taper, and will taper to the above Z value

Other parameters are available with this command but are not needed for these roughing operations.

## A.2. FACETST Part NC Programs

### A.2.1. Rough Cut NC Program for the FACETST Part

The rough cuts were divided into zones. One of these zones was chosen for ease of using the G81 canned cycle. At line N0280, rough cutting using the G81 routine is performed with 3.81 mm (0.15 inch) of metal being removed for each pass of the tool. This depth of cut is well within that permissible for the aluminum part for the feed rate used, p0.254 mm/rev (0.01 inch/rev). This second zone cut, at line N0300, removes only 3.33 mm (0.1313 inch) and is performed in a single pass. At the end of the rough cut program, the part is 0.508 mm (0.02 inches) oversize.

```
N0010  (ID, PROG,060001, Rough Cutting of FACETST)
N0020  ! Modified BAS-1 part -- Aluminum 6061-T6
N0030  ! January 20, 1995, Neil Wilkin , mod. K.Y.2/17/95
N0040  ! TOOL 3 ROUGH K68, 80 DEG., LENGTH X-5.96875.,Z-1.21875
N0050  ! ...Using Center of tool, and OFFSET X+0.1305, Z0
N0060  ! START MACHINE AT X0, Z10.
N0070  ! MDI T0, TOUCH FACE W/TOOL 3, MDI W0.71, and set Z-STARTRUFF=P41
N0080  ! RUFF FEED RATE=0.01 IN/REV
N0090  ! SEMI CUTS ARE 0.01 (0.02D) INCH OVERSIZE
N0100  ! RUFF CUTS ARE 0.02 (0.04D) INCH OVERSIZE
N0110  G70          ! Inches mode
N0120  T0300        ! Select Roughing Tool at start position of machine
N0130  T0           ! Remove tool data from controller
N0140  G94 G97 T0 M53  ! In./min., dir. rpm, no tool offsets, hi hdstk range
N0150  M03 S1200    ! Spindle on forward, set speed to 1200 rpm
N0160  G00 X0 Z(P41)  ! Move to part zero Z
N0170  G92 X30.4 Z2.0 S3000  ! Set Part zero and max spindle speed
N0180  T0300        ! Include Rough tool length in registers
N0190  G00 X6.2625 Z0.05125 T0303 M08  ! Add tool offsets, and Coolant ON
N0200  G96 S2000    ! Set CSS mode and CSS feed rate
N0210  G04 X5.0     ! Delay For Coolant And Spindle
N0220  G95          ! Inch per rev mode
N0230  G01 F.01 X-0.10 ! Rough face, past 0
N0240  G00 Z0.15125   ! Pull out
N0250  ! Zone 1 rough cuts
N0260  G00 X6.2625
N0280  M57 G81 X2.1025 Z-1.94875 F0.01 P1=0.15 P2=-1.94875 ! Cut zone 1
N0290  ! Zone 2 rough cut
N0300  G00 X6.0025 Z-1.84875  ! Goto 0.1 off face
N0310  M57 G01 Z-3.94875  ! Make cut
N0320  G01 X6.2625    ! Cut out
N0330  G94          ! Inch per minute mode
N0340  G01 F100. X30.4 Z2.0 T00 M05 M09  ! Return to register position
N0350  G92 X0 Z(P41)  ! Reset register
N0360  G00 Z10      ! Return to machine start position
N0370  M30          ! Rewind
N9999  (END, PROG)
```

### A.2.2. Semifinish Cut NC Program for the FACETST Part

Coding with parameters permitted this NC program to be used repeatedly on the same stock to cut several semifinish part sizes in the FACETST family. Lines N0012 through N0018 show the NC part program ID numbers represented, and indicate the diameter of the major cylinder used as a reference. After cutting to the first semifinish part size in the family, the part is 25.4 mm (0.01 inch) oversize.

```
N0010 (ID,PROG, 060011, Semifinish Cut: ****TST Series)
N0012 ! This file will serve the purpose of several programs:
N0013 !  060011  P46=5.90;    080011  P46=5.86;    090011  P46=5.82
N0014 !  100011  P46=5.78;    110011  P46=5.74;    120011  P46=5.70
N0015 !  130011  P46=5.66;    140011  P46=5.62;    150011  P46=5.58
N0016 !  160011  P46=5.54;    170011  P46=5.50;    180011  P46=5.46
N0017 !  190011  P46=5.42;    200011  P46=5.38;    210011  P46=5.34
N0018 !  220011  P46=5.30
N0020 ! PIECS test part -- Aluminum 6061-T6
N0030 ! January 21, 1995, Neil Wilkin , mod K.Y.2/17/95
N0040 ! TOOL 1 K68, 35 DEG., LENGTH X-5.96875.,Z-1.21875
N0050 ! ...Using Center of tool, and OFFSET X+0.128, Z0
N0060 ! START MACHINE AT X0, Z10.
N0070 ! MDI T0, TOUCH FACE W/TOOL 1, MDI W0.71, and set Z-START=P42
N0075 ! IF NO ROUGH CUT TO BE RUN, MDI W0.73 and set Z-START=P42
N0080 ! Semi Feed Rate=0.005 IN/REV
N0090 ! SEMI CUTS ARE 0.01 (0.02D) INCH OVERSIZE
N0100 ! RUFF CUTS ARE 0.02 (0.04D) INCH OVERSIZE
N0105 ! THE FOLLOWING VALUES MUST BE SET IN THE PARAMETERS TABLE:
N0106 ! P46 nominal size of larger diameter on finished part
N0107 ! P47 to taper large cylinder       P44 to taper step face
N0108 ! P48 to taper small cylinder       P45 to taper end face
N0110 G70          ! Inches mode
N0120 T0100        ! Select Finishing Tool at machine start positn
N0130 T0           ! Remove tool data from controller
N0140 G94 G97 T0 M53  ! In/min, dir rpm, no tooloffsts, hi hdstk range
N0150 M03 S3000      ! Spindle on forward, set speed to 2400 rpm
N0160 G00 X0 Z(P42)  ! Move to  Z start-semi-fin
N0170 G92 X30.4 Z2.0 S3000  ! Set Part zero and max spindle speed
N0180 T0100        ! Include Finishing tool length in registers
N0190 G00 X6.2625 Z-3.95875 T0101 M08  ! Add tool offsets; Coolant ON
N0210 G04 X5.0       ! Delay For Coolant And Spindle
N0220 G95          ! Inch per rev mode
N0230 G01 F.005 X(P46+0.0625+0.02) ! Tool nose and semifinish oversize
N0240 G01 X(P46+0.0625+0.02+P47) Z-1.95875    ! Large cyl w/ P47 taper
N0250 G01 X(P46+0.0625+0.02-3.9) Z(-1.95875+P44)!Stepface w/ P44 taper
N0260 G01 X(P46+0.0625+0.02-3.9+P48) Z0.04125 ! Small cyl w/ P48 taper
N0270 G01 X-0.03125 Z(0.04125+P45)          !  End face w/ P45 taper
N0280 G01 Z00.14125   ! To move away from the part safely
N0290 G00 X6.2625
N0300 G94          ! Inch per minute mode
N0310 G01 F100.0 X30.4 Z2.0 T00 M05 M09  ! Return to register position
N0320 G92 X0 Z(P42)  ! Reset register to Z start
N0330 G00 X0 Z10     ! Return to machine start position
N0340 M30          ! Rewind
N9999 (END, PROG)
```

### A.2.3. Finish Cut NC Programs for the FACETST part

Similar to the semifinish cut program, the finish cut program was used many times for finish cutting parts in the FACETST family during the test sequence. Lines N0012 through N0018 show the NC part program ID numbers represented, and indicate the diameter of the major cylinder used as a reference. This program is used during the error correction phase of the test cycle.

Line N0340 adjusts the location of part coordinate system for the semifinish cut of the next part size by moving the origin 0.254 mm (0.01 inch) in the negative Z direction.

```
N0010 (ID,PROG, 060021, Finish Cut: ****TST Series)
N0012 ! This file will serve the purpose of several programs:
N0013 !  060021  P46=5.90;   080021  P46=5.86;   090021  P46=5.82
N0014 !  100021  P46=5.78;   110021  P46=5.74;   120021  P46=5.70
N0015 !  130021  P46=5.66;   140021  P46=5.62;   150021  P46=5.58
N0016 !  160021  P46=5.54;   170021  P46=5.50;   180021  P46=5.46
N0017 !  190021  P46=5.42;   200021  P46=5.38;   210021  P46=5.34
N0018 !  220021  P46=5.30
N0020 ! PIECS test part -- Aluminum 6061-T6
N0030 ! Jan 21, 1995, Neil Wilkin , mod H.B.1/26/95, mod K.Y.2/17/95
N0040 ! TOOL 1 K68, 35 DEG., LENGTH X-5.96875.,Z-1.21875
N0050 ! ...Using Center of tool, and OFFSET X+0.128, Z0
N0060 ! START MACHINE AT X0, Z10.
N0080 ! Finish Feed Rate=0.005 IN/REV
N0090 ! SEMI CUTS ARE 0.01 (0.02D) INCH OVERSIZE
N0100 ! RUFF CUTS ARE 0.02 (0.04D) INCH OVERSIZE
N0105 ! THE FOLLOWING VALUES MUST BE SET IN THE PARAMETERS TABLE:
N0106 ! P46 nominal size of larger diameter on finished part
N0107 ! P47 to taper large cylinder       P44 to taper step face
N0108 ! P48 to taper small cylinder       P45 to taper end face
N0110 G70          ! Inches mode
N0120 T0100        ! Select Finishing Tool at machine start positn
N0130 T0           ! Remove tool data from controller
N0140 G94 G97 T0 M53  ! In/min, dir rpm, no tooloffsts, hi hdstk range
N0150 M03 S3000       ! Spindle on forward, set speed to 3000 rpm
N0160 G00 X0 Z(P42)   ! Move to  Z start-semi-fin
N0170 G92 X30.4 Z2.0 S3000  ! Set Part zero and max spindle speed
N0180 T0100        ! Include Finishing tool length in registers
N0190 G00 X6.2625 Z-3.96875 T0101 M08  ! Add tool offsets; Coolant ON
N0200 (UPD, 1, TOV(X), 0.00000)
N0205 (UPD, 1, TOV(Z), 0.00000)
N0210 G04 X5.0        ! Delay For Coolant And Spindle
N0220 G95          ! Inch per rev mode
N0230 G01 F.005 X(P46+0.0625) Z-3.96875
N0240 G01 X(P46+0.0625+P47) Z-1.96875       ! Large cyl with P47 taper
N0250 G01 X(P46+0.0625-3.9) Z(-1.96875+P44) ! Step face with P44 taper
```

```
N0260  G01 X(P46+0.0625-3.9+P48) Z00.03125   ! Small cyl with P48 taper
N0270  G01 X-0.03125 Z(00.03125+P45)         ! End  face with P45 taper
N0280  G01 Z00.13125   ! To move away from the part safely
N0290  G00 X6.2625
N0300  G94             ! Inch per minute mode
N0310  G01 F100.0 X30.4 Z2.0 T00 M05 M09  ! Return to register position
N0320  G92 X0 Z(P42)   ! Reset register to Z start
N0330  G00 X0 Z10      ! Return to machine start position
/N0340   P42=(P42-0.02)!Decrement Zstart-semi-fin for next cut
N0350  M30             ! Rewind
N9999  (END, PROG)
```

### A.3. MODBAS2 Part NC Programs

This part is designed to test PIECS error correction for a feature profile having an arc required to be tangent to a line.

#### A.3.1. Rough Cut NC Program for the MODBAS2 Part

The rough cuts were divided into zones chosen for ease of using the G81 canned cycle. Five (5) zones were defined. The last zone, 5, consists of 3 arc cuts (G02 command) to smooth out a portion of the partial sphere (arc). Lines N0260, N0290, N0320, and N0350 use the G81 canned cycle. The depth of the metal removed on each pass for this aluminum part is 3.81 mm (0.15 inch) at a feed rate of 0.254 mm/rev (0.01 inch/rev). The arc cuts which finish the rough cutting of the dome are located at lines N0370, N0400, and N0460. At the end of the rough cut program, the part is 0.508 mm (0.02 inches) oversize.

```
N0010  (ID,PROG, 030001, Rough Cut: MODBAS2)
N0020  ! PIECS arc error test part -- Aluminum 6061-T6
N0030  ! 6 Aug 97, Copy of program by Neil Wilkin
N0040  ! Boiler Plate by Kenneth W. Yee
N0050  ! Tool 3 rough K68, 80 deg., length X-5.96875,Z-1.21875
N0060  ! ...Using center of tool, and offset X+0, Z0
N0070  ! Start machine at X0, Z10.
N0080  ! MDI T0, touch face w/tool 3, MDI W0.71, set Z-start-ruff = P41
N0090  ! Rough feed rate=0.01 in/rev
N0100  ! The semifinish part is 0.01 (0.02 dia) inch oversize
N0110  ! The rough cut part is  0.02 (0.04 dia) inch oversize
N0120  G70             ! Inches mode
N0130  T0300           ! Select roughing tool at safe tool position
N0140  T0              ! Remove tool data from controller
N0150  G94 G97 T0 M53  ! In/min, dir rpm, no tooloffsts, hi hdstk range
N0160  M03 S1200       ! Spindle on forward, set speed to 1200 rpm
N0170  G00 X0 Z(P41)   ! Move to Z start
N0180  G92 X30.4 Z2.0 S3000  ! Set part zero and max spindle speed
```

```
N0190  T0300          ! Include roughing tool length in registers
N0200  G00 X6.2625 Z0.05125 T0303 M08 ! .1 above part, offsets, coolant
N0210  G96 S2000      ! Constant surface speed, max. spindle rpm
N0220  G04 X5.0       ! Delay for coolant and spindle
N0230  G95            ! Inch per rev mode
N0240  G01 F.01 X-0.02            ! Rough face, continue beyond axis
N0250  G00 Z0.15125               ! Pull out
N0260  ! Zone 1 rough cuts: from upper collar face forward
N0270  G00 X6.2625                ! Go to zone 1 start
N0280  M57 G81 X5.5025 Z-6.12375 F0.01 P1=0.15 P2=-6.12375 ! Cut zone 1
N0290  ! Zone 2 rough cuts: from taper forward
N0300  G00 X5.7025 Z0.15125       ! Go to zone 2 start
N0310  M57 G81 X3.7025 Z-6.12375 F0.01 P1=0.15 P2=-4.53676 ! Cut zone 2
N0320  ! Zone 3 rough cuts: from lower collar face forward
N0330  G00 X3.9025 Z0.15125       ! Go to zone 3 start
N0340  M57 G81 X3.1025 Z-1.74875 F0.01 P1=0.15 P2=-1.74875 ! Cut zone 3
N0350  ! Zone 4 rough cuts: bevel corner to prepare for arc cuts
N0360  G00 X3.3025 Z0.15125       ! Go to zone 4 start
N0370  M57 G81 X1.370 Z-0.81498 F0.01 P1=0.15 P2=0.05125   ! Cut corner
N0380  G00 Z-1.5                  ! Go to start of arc
N0390  G02 X0 Z0.15125 R1.65125     ! Cut first arc
N0400  G00 X3.2025                ! Pull out
N0410  G00 Z-1.5                  ! Go to start of arc
N0420  G02 X0 Z0.10125 R1.60125     ! Cut second arc
N0430  G00 Z0.15125               ! Pull out
N0440  G00 X3.9025                ! Go to X
N0450  G00 Z-1.74875              ! Position above lower collar
N0460  G01 X3.1025                ! Skim lower collar face
N0470  M57 G01 Z-1.5              ! Skim diameter to start of arc
N0480  M57 G02 X0 Z0.05125 R1.55125 ! Cut final rough arc
N0490  M57 G01 X-0.02             ! Continue beyond axis
N0500  G00 Z0.15125               ! Pull out
N0510  ! Zone 5 rough cuts: upper collar diameter, just inside stock
N0520  G00 X5.9025                ! Go to X start for zone 5
N0530  G00 Z-6.0238               ! Go to 0.1 off upper collar face
N0540  G01 Z-6.42375              ! Cut upper collar diameter
N0550  M57 G01 X6.2625            ! Cut upward out of stock
N0560  G94            ! Inch per minute mode
N0570  G01 F100.0 X30.4 Z2.0 T00 M05 M09  ! Return to register position
N0580  G92 X0 Z(P41)   ! Reset register to Z start
N0590  G00 X0 Z10      ! Return to safe tool position
N0600  M30            ! Rewind
N9999  (END, PROG)
```

### A.3.2. Semifinish Cut NC Program for the MODBAS2 Part

Coding with parameters permitted this NC program to be used repeatedly on the same stock to cut several semifinish part sizes in the MODBAS2 family. Lines N0012 through N0018 show the NC part program ID numbers represented, and indicate the diameter of the major cylinder used as a reference.

```
N0010 (ID,PROG, 030011, Semifinish Cut: MOD**S* Series)
N0020 ! This file will serve the purpose of several programs:
N0030 !  030021 P46=3.60;   240021 P46=3.56;   250021 P46=3.52
N0040 !  260021 P46=3.48;   270021 P46=3.44;   280021 P46=3.40
N0050 !  290021 P46=3.36;   300021 P46=3.32;   310021 P46=3.28
N0060 !  320021 P46=3.24;   330021 P46=3.20;   340021 P46=3.16
N0070 !  350021 P46=3.12    360021 P46=3.08;   370021 P46=3.04
N0080 !  380021 P46=3.00
N0090 ! PIECS arc error test part -- Aluminum 6061-T6
N0100 ! 17 Apr 97, Herbert T. Bandy
N0110 ! Boiler Plate by Kenneth W. Yee
N0120 ! Tool 1 K68, 35 deg., length X-5.96875,Z-1.21875
N0130 ! ...Using center of tool, and offset X+0, Z0
N0140 ! Start machine at X0, Z10.
N0150 ! MDI T0, touch face w/tool 1, MDI W0.71, and set Z-start = P42
N0155 ! If no rough cut to be run, MDI W0.73 and set Z-start = P42
N0160 ! Semifinish feed rate=0.005 in/rev
N0170 ! The semifinish part is 0.01 (0.02 dia) inch oversize
N0180 ! The rough cut part is  0.02 (0.04 dia) inch oversize
N0190 ! THE FOLLOWING VALUES MUST BE SET IN THE PARAMETERS TABLE:
N0200 ! P46 nominal diameter of main cylinder on finished part
N0210 ! P47 delta Z mock error at base of taper at main cylinder
N0220 G70          ! Inches mode
N0230 T0100        ! Select semifinish tool at safe tool position
N0240 T0           ! Remove tool data from controller
N0250 G94 G97 T0 M53  ! In/min, dir rpm, no tooloffsts, hi hdstk range
N0260 M03 S3000      ! Spindle on forward, set speed to 3000 rpm
N0270 G00 X0 Z(P42)   ! Move to Z start
N0280 G92 X30.4 Z2.0  ! Set part zero and max spindle speed
N0290 T0100        ! Include semifinish tool length in registers
N0295 G00 X6.2625 Z-6.53375 T0101 M08  ! Add tool offsets; coolant ON
N0300 G00 X6.2625 Z(-6.43375+(3.6-P46)/2) ! start without backlash
N0330 G04 X5.0       ! Delay for coolant and spindle
N0340 G95          ! Inch per rev mode
N0350 G01 F0.005 X(P46+2.2+0.0625+0.02)  Z(-6.43375+(3.6-P46)/2)
N0360 G01        X(P46+2.2+0.0625+0.02)  Z(-6.13375+(3.6-P46)/2)
N0370 G01        X(P46+1.8+0.04862)      Z(-6.13375+(3.6-P46)/2)
N0380 G01        X(P46+0.0625+0.02)      Z(-4.53934+P47+(3.6-P46)/2)
N0390 G01        X(P46+0.0625+0.02)      Z(-1.75875+(3.6-P46)/2)
N0400 G01        X(P46-0.6+0.0625+0.02)  Z(-1.75875+(3.6-P46)/2)
```

```
N0410  G01       X(P46-0.6+0.0625+0.02)  Z(-1.50000+(3.6-P46)/2)
N0420  G02       X0.00000 Z00.04125 F0.005 R(P46/2-0.3+0.03125+0.01)
N0430  G01       X-.06250 Z00.04125            ! Beyond axis
N0440  G00 Z0.13125   ! Move away from part safely
N0450  G00 X6.2625
N0460  G94          ! Inch per minute mode
N0470  G01 F100.0 X30.4 Z2.0 T00 M05 M09  ! Return to register position
N0480  G92 X0 Z(P42)   ! Reset register to Z start
N0490  G00 X0 Z10     ! Return to safe tool position
N0510  M30          ! Rewind
N9999  (END, PROG)
```

### A.3.3. Finish Cut NC Program for the MODBAS2 Part

In this finish cut program, line N0500 has a backslash character before the line number. This is a *block delete* command. There is a button on the NC controller which permits skipping this line during the execution of this program. That button MUST be turned on for this sequence since a pre-semifinish cut program (see below) is used to prepare for the next cut sequence.

```
N0010  (ID,PROG, 030021, Finish Cut: MOD**S* Series)
N0020  ! This file will serve the purpose of several programs:
N0030  !  030021  P46=3.60;    240021  P46=3.56;    250021  P46=3.52
N0040  !  260021  P46=3.48;    270021  P46=3.44;    280021  P46=3.40
N0050  !  290021  P46=3.36;    300021  P46=3.32;    310021  P46=3.28
N0060  !  320021  P46=3.24;    330021  P46=3.20;    340021  P46=3.16
N0070  !  350021  P46=3.12     360021  P46=3.08;    370021  P46=3.04
N0080  !  380021  P46=3.00
N0090  ! PIECS arc error test part -- Aluminum 6061-T6
N0100  ! 17 Apr 97, Herbert T. Bandy
N0110  ! Boiler Plate by Kenneth W. Yee
N0120  ! Tool 1 K68, 35 deg., length X-5.96875,Z-1.21875
N0130  ! ...Using center of tool, and offset X+0, Z0
N0140  ! Start machine at X0, Z10.
N0160  ! Finish feed rate=0.005 in/rev
N0170  ! The semifinish part is 0.01 (0.02 dia) inch oversize
N0180  ! The rough cut part is  0.02 (0.04 dia) inch oversize
N0190  ! THE FOLLOWING VALUES MUST BE SET IN THE PARAMETERS TABLE:
N0200  ! P46 nominal diameter of main cylinder on finished part
N0210  ! P47 delta Z mock error at base of taper at main cylinder
N0220  G70          ! Inches mode
N0230  T0100         ! Select finishing tool at safe tool position
N0240  T0           ! Remove tool data from controller
N0250  G94 G97 T0 M53  ! In/min, dir rpm, no tooloffsts, hi hdstk range
N0260  M03 S3000      ! Spindle on forward, set speed to 3000 rpm
N0270  G00 X0 Z(P42)   ! Move to Z start from semifinish part
N0280  G92 X30.4 Z2.0  ! Set part zero and max spindle speed
```

```
N0290  T0100          ! Include finishing tool length in registers
N0295  G00 X6.2625 Z-6.54375 T0101 M08  ! Add tool offsets; coolant ON
N0300  G00 X6.2625 Z(-6.44375+(3.6-P46)/2) ! avoid backlash for softwr
N0310  (UPD, 1, TOV(X), 0.00000)
N0320  (UPD, 1, TOV(Z), 0.00000)
N0330  G04 X5.0       ! Delay for coolant and spindle
N0340  G95            ! Inch per rev mode
N0350  G01 F0.005 X(P46+2.2+0.0625)  Z(-6.44375+(3.6-P46)/2) ! To collr
N0360  G01       X(P46+2.2+0.0625)  Z(-6.14375+(3.6-P46)/2) ! Cut coll
N0370  G01       X(P46+1.8+0.03684) Z(-6.14375+(3.6-P46)/2) ! To taper
N0380  G01       X(P46+0.0625)      Z(-4.54192+P47+(3.6-P46)/2)! Taper
N0390  G01       X(P46+0.0625)      Z(-1.76875+(3.6-P46)/2) ! Cut cyl
N0400  G01       X(P46-0.6+0.0625)  Z(-1.76875+(3.6-P46)/2) ! To collr
N0410  G01       X(P46-0.6+0.0625)  Z(-1.50000+(3.6-P46)/2) ! To arc
N0420  G02       X0.00000 Z00.03125 F0.005 R(P46/2-0.3+0.03125)! Arc
N0430  G01       X-.06250 Z00.03125          ! Continue beyond axis
N0440  G00 Z0.13125    ! Move away from part safely
N0450  G00 X6.2625
N0460  G94            ! Inch per minute mode
N0470  G01 F100.0 X30.4 Z2.0 T00 M05 M09  ! Return to register position
N0480  G92 X0 Z(P42)   ! Reset register to Z start
N0490  G00 X0 Z10      ! Return to safe tool position
/N0500  P42=(P42-0.02)!Decrement Z start for next semifinish part
N0510  M30            ! Rewind
N9999  (END, PROG)
```

### A.3.4. Pre-Semifinish Cut Program for the MODBAS2 Part

This program is executed after making the finish cut on the last part, in preparation for making the semifinish cut for the next smaller part size in the MODBAS2 family. This program performs a cut operation to move the center of the arc to the correct location to correspond to a reduction in diameter of 0.508 mm (0.02 inch). If the Z dimensions are held constant as the part is reduced in diameter, the arc is no longer a true arc. A machining step needs to ensure that the arc is circular rather than elliptical. To accomplish this, the center of the arc is moved the same distance that the diameter of the part is reduced. In addition, after each test sequence the part origin is also moved 0.508 mm (0.02 inch) in the minus Z direction. Thus line N0500 decrements the Z value of the part zero by the 1.016 mm (0.04 inch) after the cut performed by this program, in preparation for the next semifinish cut for the next part sequence. This method of efficiently using a single stock for cutting multiple parts was suggested by one of the authors (M. Kennedy).

```
N0010  (ID,PROG, 030031, Pre-semi Cut: MOD**S* Series)
N0020  ! This file will serve the purpose of several programs:
N0030  !  030021  P46=3.60;   240021  P46=3.56;   250021  P46=3.52
N0040  !  260021  P46=3.48;   270021  P46=3.44;   280021  P46=3.40
N0050  !  290021  P46=3.36;   300021  P46=3.32;   310021  P46=3.28
N0060  !  320021  P46=3.24;   330021  P46=3.20;   340021  P46=3.16
```

```
N0070 !  350021  P46=3.12     360021  P46=3.08;    370021  P46=3.04
N0080 !  380021  P46=3.00
N0090 ! PIECS arc error test part -- Aluminum 6061-T6
N0100 ! 17 Apr 97, Herbert T. Bandy
N0110 ! Boiler Plate by Kenneth W. Yee
N0120 ! Tool 1 K68, 35 deg., length X-5.96875,Z-1.21875
N0130 ! ...Using center of tool, and offset X+0, Z0
N0140 ! Start machine at X0, Z10.
N0160 ! Finish feed rate=0.005 in/rev
N0170 ! The semifinish part is 0.01 (0.02 dia) inch oversize
N0180 ! The rough cut part is  0.02 (0.04 dia) inch oversize
N0190 ! THE FOLLOWING VALUES MUST BE SET IN THE PARAMETERS TABLE:
N0200 ! P46 nominal diameter of main cylinder on finished part
N0210 ! P47 delta Z mock error at base of taper at main cylinder
N0220 G70           ! Inches mode
N0230 T0100         ! Select finishing tool at safe tool position
N0240 T0            ! Remove tool data from controller
N0250 G94 G97 T0 M53  ! In/min, dir rpm, no tooloffsts, hi hdstk range
N0260 M03 S3000      ! Spindle on forward, set speed to 3000 rpm
N0270 G00 X0 Z(P42)   ! Move to Z start from semifinish part
N0280 G92 X30.4 Z2.0  ! Set part zero and max spindle speed
N0290 T0100         ! Include finishing tool length in registers
N0295 G00 X6.2625 Z-6.54375 T0101 M08  ! Add tool offsets; coolant ON
N0300 G00 X6.2625 Z(-6.44375+(3.6-P46)/2) ! avoid backlash for softwr
N0310 (UPD, 1, TOV(X), 0.00000)
N0320 (UPD, 1, TOV(Z), 0.00000)
N0330 G04 X5.0       ! Delay for coolant and spindle
N0340 G95           ! Inch per rev mode
N0350 G01 F0.005 X(P46+2.2+0.0625)  Z(-6.44375+(3.6-P46)/2) ! To collr
N0360 G01       X(P46+2.2+0.0625)  Z(-6.14375+(3.6-P46)/2) ! Cut coll
N0370 G01       X(P46+1.8+0.03684) Z(-6.14375+(3.6-P46)/2) ! To taper
N0380 G01       X(P46+0.0625)      Z(-4.54192+P47+(3.6-P46)/2)! Taper
N0390 G01       X(P46+0.0625)      Z(-1.76875+(3.6-P46)/2) ! Cut cyl
N0400 G01       X(P46-0.6+0.0625)  Z(-1.76875+(3.6-P46)/2) ! To collr
N0410 G01       X(P46-0.6+0.0625)  Z(-1.52000+(3.6-P46)/2) ! To arc
N0420 G02       X0.00000 Z00.01125 F0.005 R(P46/2-0.3+0.03125)! Arc
N0430 G01       X-.06250 Z00.01125          ! Continue beyond axis
N0440 G00 Z0.13125    ! Move away from part safely
N0450 G00 X6.2625
N0460 G94           ! Inch per minute mode
N0470 G01 F100.0 X30.4 Z2.0 T00 M05 M09  ! Return to register position
N0480 G92 X0 Z(P42)   ! Reset register to Z start
N0490 G00 X0 Z10      ! Return to safe tool position
/N0500  P42=(P42-0.04)!Decrement Z start for next semifinish part
N0510 M30           ! Rewind
N9999 (END, PROG)
```

## A.4. PIECS11 Part NC Programs

### A.4.1. Rough Cut NC Program for the PIECS11 Part

This NC program is written as two programs combined together as one. At the junction between the spherical feature and the tapered cone, the geometry is such that the roughing tool shape cannot be used without gouging the partial sphere with the roughing tool. Since this will occur only for rough cutting, and will not have any bearing on the semifinish and finish cuts, the roughing program was written to ignore that portion of the part during the use of the roughing tool. The rough cuts were divided into zones chosen for ease of using the G81 canned cycle. Five (5) zones were defined. The last zone, 5, consists of 3 arc cuts (G02 command) to smooth out a portion of the partial sphere. In the area where the taper and sphere intersect, metal remains to be removed, requiring a cut of a maximum of 1.524 mm (0.060 inches), so a tool change is necessary. This depth of cut is well within that permissible for the aluminum part for the feed rate used, 0.127 mm/rev (0.005 inch/rev). At the end of the rough cut program, the part is 0.762 mm (0.03 inches) oversize. A skim cut program using the semifinish tool was written and added to the end of the zones roughing program. This portion of the NC program completes the rough cuts (starting at line N0590). The program pauses the machine between these two rough cut segments. This pause is for the convenience of the operator of the turning center. When the rough cut program is finished, the part will be 0.79 mm (0.020 inch) oversize.

```
N0010  (ID,PROG, 350001, Rough Cut: PIECS11)
N0020  ! PIECS11 part -- Aluminum 6061-T6
N0030  ! December 3, 1997,  Neil D. Wilkin
N0040  ! Used in PIECS program
N0050  ! TOOL 3 ROUGH K68, 80 DEG., LENGTH X-5.96875.,Z-1.21875
N0060  ! ...OFFSET X+0.133, Z0 depending on specific tool insert
N0070  ! START MACHINE AT X0, Z10.
N0080  ! Touch Face with tool 3, MDI W0.71, To set Z at part zero=P41=_______
N0090  ! Touch Face with tool 1, MDI W0.71 also, set Z = P42=_____________
N0100  ! RUFF FEED RATE=0.01 IN/REV
N0110  ! RUFF CUTS ARE 0.02 (0.06D) INCH OVERSIZE
N0120  G70  ! Inches mode
N0130  G94 G97 T0 M53  ! In./min., dir. rpm, no tool offsets, hi hdstk range
N0140  T0300 ! Select roughing tool in safe place
N0150  T0 ! Remove offsets
N0160  M03 S1200  ! Spindle on forward, set speed to 1200 rpm
N0170  G00 X0 Z(P41)  ! Move to part zero Z
N0180  G92 X30.4 Z2.0 S3000  ! PART POSITION RE Part zero
N0190  T0300  ! RUFFING TOOL
N0200  G00 X6.2625 Z0.05125 T0303 M08  ! 0.1 OFF PART, set cut 0.02, COOL ON
N0210  G96 S2000  ! CONSTANT SURFACE SPEED, max. spindle rpm
N0220  G04 X5.0  ! DELAY FOR COOLANT AND SPINDLE
N0230  G95  ! Inch per rev
N0240  G01 F.01 X-0.02 ! Rough face, past 0
N0250  G00 Z0.15125 ! Pull out
```

```
N0260  ! Zone 1 rough cuts
N0270  G00 X6.2625 Z0.15125
N0280  M57 G81 X5.42250 Z-4.18875 F0.01 P1=0.15 P2=-4.18875 ! Cut zone 1
N0290  ! Zone 2 rough cuts
N0300  G00 X5.66500 Z0.15125 ! Go to start
N0310  M57 G81 X4.87128 Z-3.68875 F0.01 P1=0.15 P2=-3.68875 ! Cut zone 2
N0320  ! Zone 3 rough cuts
N0330  G00 X5.09602 Z0.15125 ! Go to start
N0340  M57 G81 X2.62250 Z-3.68875 F0.01 P1=0.15 P2=-1.71013 ! Cut zone 3
N0350  ! Zone 4 rough cuts
N0360  G00 X2.82250 Z0.15125 ! Go to starting point for zone 4
N0370  M57 G81 X0.97802 Z-0.61055 F0.01 P1=0.15 P2=0.05125 ! Knock off corner
N0380 ! Zone 5 cuts
N0390  G00 X2.96250 Z-1.25000 ! Go to near start of 1st arc
N0400  G01 X2.76250 Z-1.25000 ! Go to start of 1st arc
N0410 M57 G02 X0.00000 Z0.13125 R1.38125 F0.005 ! Cut 1st arc
N0420  G00 Z0.15125  ! Pull out
N0430  G00 X2.96250 ! Clear dome
N0440  G00 X2.96250 Z-1.25000 ! Go to near start of 2nd arc
N0450  G01 X2.69250 Z-1.25000 ! Go to start of 2nd arc
N0460 M57 G02 X0.00000 Z0.09625 R1.34625 F0.005 ! Cut 2nd arc
N0470  G00 Z0.15125  ! Pull out
N0480  G00 X2.96250 ! Clear dome
N0490  G00 X2.96250 Z-1.25000 ! Go to near start of 3rd arc
N0500  G01 X2.62250 Z-1.25000 ! Go to start of 3rd arc
N0510 M57 G02 X0.00000 Z0.06125 R1.31125 F0.005 ! Cut 3rd arc
N0520  G00 Z0.15125  ! Pull out
N0530  G00 X6.26250 ! Clear part
N0540  G94 G97 S2000! Change  to inch per minute, 2000 rpm
N0550  G01 F100. X30.4 Z2. T0!
N0560  G92 X0 Z(P41)  ! BACK TO MACHINE POSITION
N0570  G00 X0 Z10  ! TO START MACHINE point
N0580  !
N0590  ! Reset machine to select new tool.
N0600  M00 ! Pause Machine /Turn off spindle
N0610  T0100  ! Change to Finishing Tool
N0620  T0 ! Remove offsets
N0630  G00 X0 Z(P42)  ! Move to part zero Z face point
N0640  G92 X30.4 Z2.0  ! Set part zero
N0650 M03 S3000 ! Start spindle again
N0660 G95 ! Change to inch per rev
N0670  G00 X6.26250 Z-4.29875 T0101 M08 ! Remove Backlash
N0680 G04 X5.0 ! Delay for spindle start
N0690  G00 X6.26250 Z-4.19875 ! Go to start
N0700  G01 X5.40250 Z-4.19875 F0.005 ! Cut
N0710  G01 X5.40250 Z-3.69875 ! Cut
N0720  G01 X4.85964 Z-3.69875 ! Cut
```

```
N0730  G01 X2.49576 Z-1.61885 ! Cut to arc start
N0740  M57 G02 X0.00000 Z0.05125 F0.005 I-1.24788 K0.36885 ! Cut  arc
N0750  M57 G01 X-0.05000 Z0.05125 ! Cut past nose
N0760  G00 Z0.15125 ! Pull out
N0770  G00 X6.26250 ! Clear part
N0780  G94 ! Change  to inch per minute
N0790  G01 F100. X30.4 Z2. T00 M05 M09  ! Reset to Machine
N0800  G92 X0.00000 Z(P42)  ! Parameters, HERE
N0810  G00 X0.00000 Z10.00000  ! To Machine Home
N0820  M30  ! Rewind
N9999  (END, PROG)
```

### A.4.2. Semifinish Cut and Finish Cut NC Programs for the PIECS11 Part

These NC programs are identical in terms of function, and each removes 0.0254 mm (0.01 inch) of material from all surfaces of the part. The program cuts in a clockwise direction (-Z, +X) for the complete pass. The initial location to which the tool moves is 2.54 mm (0.1 inch) in the Z direction from the entrance cut on the part. This permits removing the Z backlash in the machine axes before cutting begins.

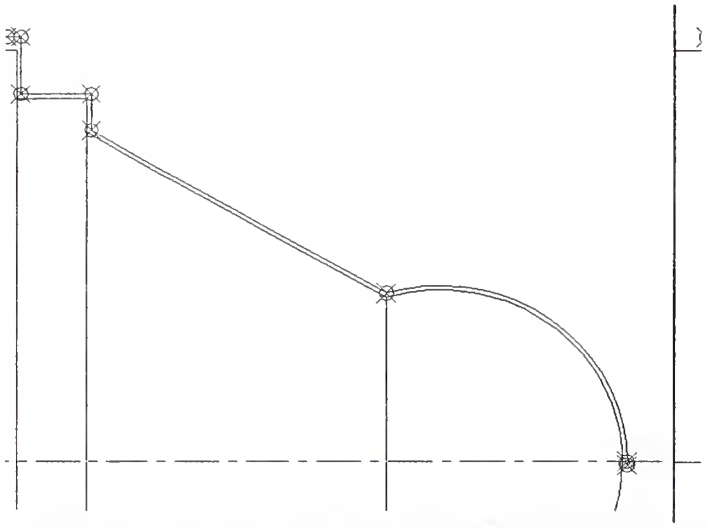

**Figure 18: Semifinish and Finish Profiles for PIECS11**

The main difference between the programs other than the programmed points is that the finish cut program will index the Z location of part zero after the finish cut is made. The programs are to be used in sequence as shown below. The calculated points used to generate the programs are included before each program.

### A.4.2.1. First Part in the PIECS11 Family, Semifinish Cut Points

Semifinish cuts.

Diameter = 5.30000

Start

at point 1, X= 6.26250 Z= -4.30875

at point 2, X= 6.26250 Z= -4.20875

at point 3, X= 5.38250 Z= -4.20875

at point 4, X= 5.38250 Z= -3.70875

at point 5, X= 4.84800 Z= -3.70875

at point 6, X= 2.47416 Z= -1.62009

at point 7, X= 0.00000 Z= 0.04125

at point 8, X= -0.05000 Z= 0.04125

arc center X= 0.00000 Z= -1.25000

arc radius 1.29125

arc center offset I = -1.23708 K = 0.37009

### A.4.2.2. First Part in the PIECS11 Family, Semifinish Cut Program

```
N0010 (ID,PROG, 350011, Semifinish Cut: PIECS11)
N0020 ! The following are values to change part size as needed:
N0030 ! Diameter 5.30 program
N0040 ! PIECS11 part -- Aluminum 6061-T6
N0050 ! Designed and written by Neil D. Wilkin
N0060 ! February 2, 1998
N0070 ! Tool 1 K68, 35 deg., length X-5.96875, Z-1.21875
N0080 ! ...Using center of tool, and offset X+_____, Z0
N0090 ! Start machine at X0, Z10.
N0100 ! MDI T0, touch face w/tool 1, MDI W0.71, and set Z-start = P42
N0110 ! If no rough cut to be run, MDI W0.73 and set Z-start = P42
N0120 ! Semifinish feed rate=0.005 in/rev
N0130 ! The semifinish part is 0.01 (0.02 dia) inch oversize
```

```
N0140 !
N0150 G70      ! Inches mode
N0160 T0100   ! Select tool at turret home position
N0170 T0       ! Remove tool offsets, after selecting tool
N0180 ! Start Machining here....
N0190 G94 G97 T0 M53  ! In/min, dir rpm, no tool offsets, high spindle range
N0200 M03 S3000      ! Spindle on forward, set speed to 3000 rpm
N0210 G00 X0 Z(P42)   ! Move to Z start
N0220 G92 X30.4 Z2.0  ! Set part zero and max spindle speed
N0230 T0100          ! Apply tool lengths
N0240 G00 X6.2625 Z-4.30875 T0101 M08  ! Go to Start, apply tool offsets; coolant ON
N0250 G00 X6.2625 Z-4.20875 ! Z move to remove backlash
N0260 G04 X5.0       ! Delay for coolant and spindle
N0270 G95            ! Inch per rev mode
N0280 G01 F0.005 X5.38250  Z-4.20875 ! To upper collar
N0290 G01 X5.38250  Z-3.70875 ! Cut upper collar
N0300 G01 X4.84800 Z-3.70875 ! To start of taper
N0310 G01 X2.47416  Z-1.62009 ! Taper and start of arc
N0320 G02 X0.00000 Z0.04125 F0.005 I-1.23708 K0.37009 ! Cut arc
N0330 G01 X-0.05000 Z0.04125   ! Beyond axis
N0340 G00 Z0.14125  ! Clear part in Z
N0350 G00 X6.2625   ! Clear part in X
N0360 G94            ! Inch per minute mode
N0370 G01 F100.0 X30.4 Z2.0 T00 M05 M09  ! Reset all registers
N0380 G92 X0 Z(P42)   ! Reset register to machine values
N0390 G00 X0 Z10      ! Return home
N0400 M30             ! Rewind
N9999 (END, PROG)
```

### A.4.2.3. First Part in the PIECS11 Family, Finish Cut Points

Finish cuts.

Diameter = 5.30000

Start

at point 1, X= 6.26250 Z= -4.31875

at point 2, X= 6.26250 Z= -4.21875

at point 3, X= 5.36250 Z= -4.21875

at point 4, X= 5.36250 Z= -3.71875

at point 5, X= 4.83636 Z= -3.71875

at point 6, X= 2.45254 Z= -1.62131

at point 7, X= 0.00000 Z= 0.03125

at point 8, X= -0.05000 Z= 0.03125

arc center X= 0.00000 Z= -1.25000

arc radius 1.28125

arc center offset I = -1.22627 K = 0.37131

### A.4.2.4. First Part in the PIECS11 Family, Finish Cut Program

```
N0010 (ID,PROG, 350021, Finish Cut: PIECS11)
N0020 ! The following are values to change part size as needed:
N0030 ! Diameter 5.30 program
N0040 ! PIECS11 part -- Aluminum 6061-T6
N0050 ! Designed and written by Neil D. Wilkin
N0060 ! February 2, 1998
N0070 ! Tool 1 K68, 35 deg., length X-5.96875, Z-1.21875
N0080 ! ...Using center of tool, and offset X+_____, Z0
N0090 ! Start machine at X0, Z10.
N0100 ! MDI T0, touch face w/tool 1, MDI W0.71, and set Z-start = P42
N0110 ! If no rough cut to be run, MDI W0.73 and set Z-start = P42
N0120 ! Finish feed rate=0.005 in/rev
N0130 ! The semifinish part is 0.01 (0.02 dia) inch oversize
N0140 !
N0150 G70          ! Inches mode
N0160 T0100        ! Select tool at turret home position
N0170 T0           ! Remove tool offsets, after selecting tool
N0180 ! Start Machining here....
N0190 G94 G97 T0 M53  ! In/min, dir rpm, no tooloffsts, hi spndl range
N0200 M03 S3000      ! Spindle on forward, set speed to 3000 rpm
N0210 G00 X0 Z(P42)   ! Move to Z start
N0220 G92 X30.4 Z2.0  ! Set part zero and max spindle speed
N0230 T0100          ! Apply tool lengths
N0240 G00 X6.2625 Z-4.31875 T0101 M08  ! Add tool offsets; Coolant ON
N0244 (UPD, 1, TOV(X), 0.00000)
N0245 (UPD, 1, TOV(Z), 0.00000)
N0250 G00 X6.2625 Z-4.21875 ! Z move to remove backlash
N0260 G04 X5.0       ! Delay for coolant and spindle
N0270 G95            ! Inch per rev mode
```

```
N0280  G01 F0.005 X5.36250  Z-4.21875 ! To upper collar
N0290  G01       X5.36250  Z-3.71875 ! Cut upper collar
N0300  G01       X4.83636  Z-3.71875 ! To start of taper
N0310  G01       X2.45254  Z-1.62131 ! Taper and start of arc
N0320  G02       X0.00000  Z0.03125 F0.005 I-1.22627 K0.37131 ! Arc
N0330  G01       X-0.05000 Z0.03125  ! Beyond axis
N0340  G00 Z0.14125    ! Clear part in Z
N0350  G00 X6.2625     ! Clear part in X
N0360  G94             ! Inch per minute mode
N0370  G01 F100.0 X30.4 Z2.0 T00 M05 M09  ! Reset all registers
N0380  G92 X0 Z(P42)   ! Reset register to machine values
N0390  G00 X0 Z10      ! Return home
/N0400   P42=(P42-0.02)! Decrement part zero for next series of cuts
N0410  M30             ! Rewind
N9999  (END, PROG)
```

### A.4.2.5. Second Part in the PIECS11 Family, Semifinish Cut Points

Semifinish cuts.

Diameter = 5.26000

Start

at point 1, X= 6.26250 Z= -4.30875

at point 2, X= 6.26250 Z= -4.20875

at point 3, X= 5.34250 Z= -4.20875

at point 4, X= 5.34250 Z= -3.70875

at point 5, X= 4.82474 Z= -3.70875

at point 6, X= 2.43090 Z= -1.60251

at point 7, X= 0.00000 Z= 0.04125

at point 8, X= -0.05000 Z= 0.04125

arc center X= 0.00000 Z= -1.23000

arc radius 1.27125

arc center offset I = -1.21545 K = 0.37251

### A.4.2.6. Second Part in the PIECS11 Family, Semifinish Cut Program

```
N0010 (ID,PROG, 360011, Semifinish Cut: PIECS21)
N0020 ! The following are values to change part size as needed:
N0030 ! Diameter 5.26 program
N0040 ! PIECS21 part -- Aluminum 6061-T6
N0050 ! Designed and written by Neil D. Wilkin
N0060 ! February 2, 1998
N0070 ! Tool 1 K68, 35 deg., length X-5.96875, Z-1.21875
N0080 ! ...Using center of tool, and offset X+_____, Z0
N0090 ! Start machine at X0, Z10.
N0100 ! MDI T0, touch face w/tool 1, MDI W0.71, and set Z-start = P42
N0110 ! If no rough cut to be run, MDI W0.73 and set Z-start = P42
N0120 ! Semifinish feed rate=0.005 in/rev
N0130 ! The semifinish part is 0.01 (0.02 dia) inch oversize
N0140 !
N0150 G70      ! Inches mode
N0160 T0100    ! Select tool at turret home position
N0170 T0       ! Remove tool offsets, after selecting tool
N0180 ! Start Machining here....
N0190 G94 G97 T0 M53  ! In/min, dir rpm, no tool offsets, high spindle range
N0200 M03 S3000      ! Spindle on forward, set speed to 3000 rpm
N0210 G00 X0 Z(P42)   ! Move to Z start
N0220 G92 X30.4 Z2.0  ! Set part zero and max spindle speed
N0230 T0100          ! Apply tool lengths
N0240 G00 X6.2625 Z-4.30875 T0101 M08  ! Go to Start, apply tool offsets; coolant ON
N0250 G00 X6.2625 Z-4.20875 ! Z move to remove backlash
N0260 G04 X5.0       ! Delay for coolant and spindle
N0270 G95            ! Inch per rev mode
N0280 G01 F0.005 X5.34250  Z-4.20875 ! To upper collar
N0290 G01 X5.34250  Z-3.70875 ! Cut upper collar
N0300 G01 X4.82474 Z-3.70875 ! To start of taper
N0310 G01 X2.43090  Z-1.60251 ! Taper and start of arc
N0320 G02 X0.00000 Z0.04125 F0.005 I-1.21545 K0.37251 ! Cut arc
N0330 G01 X-0.05000 Z0.04125   ! Beyond axis
N0340 G00 Z0.14125  ! Clear part in Z
N0350 G00 X6.2625   ! Clear part in X
N0360 G94            ! Inch per minute mode
N0370 G01 F100.0 X30.4 Z2.0 T00 M05 M09  ! Reset all registers
N0380 G92 X0 Z(P42)  ! Reset register to machine values
N0390 G00 X0 Z10      ! Return home
N0400 M30             ! Rewind
N9999 (END, PROG)
```

### A.4.2.7. Second Part in the PIECS11 Family, Finish Cut Points

Finish cuts.

Diameter = 5.26000

Start

at point 1, X= 6.26250 Z= -4.31875

at point 2, X= 6.26250 Z= -4.21875

at point 3, X= 5.32250 Z= -4.21875

at point 4, X= 5.32250 Z= -3.71875

at point 5, X= 4.81310 Z= -3.71875

at point 6, X= 2.40924 Z= -1.60369

at point 7, X= 0.00000 Z= 0.03125

at point 8, X= -0.05000 Z= 0.03125

arc center X= 0.00000 Z= -1.23000

arc radius 1.26125

arc center offset I = -1.20462 K = 0.37369

### A.4.2.8. Second Part in the PIECS11 Family, Finish Cut Program

```
N0010 (ID,PROG, 360021, Finish Cut: PIECS21)
N0020 ! The following are values to change part size as needed:
N0030 ! Diameter 5.26 program
N0040 ! PIECS21 part -- Aluminum 6061-T6
N0050 ! Designed and written by Neil D. Wilkin
N0060 ! February 2, 1998
N0070 ! Tool 1 K68, 35 deg., length X-5.96875, Z-1.21875
N0080 ! ...Using center of tool, and offset X+_____, Z0
N0090 ! Start machine at X0, Z10.
N0100 ! MDI T0, touch face w/tool 1, MDI W0.71, and set Z-start = P42
N0110 ! If no rough cut to be run, MDI W0.73 and set Z-start = P42
N0120 ! Finish feed rate=0.005 in/rev
N0130 ! The semifinish part is 0.01 (0.02 dia) inch oversize
```

```
N0140  !
N0150  G70          ! Inches mode
N0160  T0100        ! Select tool at turret home position
N0170  T0           ! Remove tool offsets, after selecting tool
N0180  ! Start Machining here....
N0190  G94 G97 T0 M53  ! In/min, dir rpm, no tooloffsts, hi spndl range
N0200  M03 S3000       ! Spindle on forward, set speed to 3000 rpm
N0210  G00 X0 Z(P42)   ! Move to Z start
N0220  G92 X30.4 Z2.0  ! Set part zero and max spindle speed
N0230  T0100           ! Apply tool lengths
N0240  G00 X6.2625 Z-4.31875 T0101 M08  ! Add tool offsets; Coolant ON
N0244  (UPD, 1, TOV(X), 0.00000)
N0245  (UPD, 1, TOV(Z), 0.00000)
N0250  G00 X6.2625 Z-4.21875 ! Z move to remove backlash
N0260  G04 X5.0        ! Delay for coolant and spindle
N0270  G95             ! Inch per rev mode
N0280  G01 F0.005 X5.32250  Z-4.21875 ! To upper collar
N0290  G01        X5.32250  Z-3.71875 ! Cut upper collar
N0300  G01        X4.81310  Z-3.71875 ! To start of taper
N0310  G01        X2.40924  Z-1.60369 ! Taper and start of arc
N0320  G02        X0.00000  Z0.03125 F0.005 I-1.20462 K0.37369 ! Arc
N0330  G01        X-0.05000 Z0.03125  ! Beyond axis
N0340  G00 Z0.14125    ! Clear part in Z
N0350  G00 X6.2625     ! Clear part in X
N0360  G94             ! Inch per minute mode
N0370  G01 F100.0 X30.4 Z2.0 T00 M05 M09  ! Reset all registers
N0380  G92 X0 Z(P42)   ! Reset register to machine values
N0390  G00 X0 Z10      ! Return home
/N0400   P42=(P42-0.02)! Decrement part zero for next series of cuts
N0410  M30             ! Rewind
N9999  (END, PROG)
```

### A.4.2.9. Third Part in the PIECS11 Family, Semifinish Cut Points

Semifinish cuts.

Diameter = 5.22000

Start

at point 1, X= 6.26250 Z= -4.30875

at point 2, X= 6.26250 Z= -4.20875

at point 3, X= 5.30250 Z= -4.20875

at point 4, X= 5.30250 Z= -3.70875

at point 5, X= 4.80146 Z= -3.70875

at point 6, X= 2.38756 Z=-1.58486

at point 7, X= 0.00000 Z= 0.04125

at point 8, X= -0.05000 Z= 0.04125

arc center X= 0.00000 Z= -1.21000

arc radius 1.25125

arc center offset I = -1.19378 K = 0.37486

### A.4.2.10. Third Part in the PIECS11 Family, Semifinish Cut Program

```
N0010 (ID,PROG, 370011, Semifinish Cut: PIECS31)
N0020 ! The following are values to change part size as needed:
N0030 ! Diameter 5.22 program
N0040 ! PIECS31 part -- Aluminum 6061-T6
N0050 ! Designed and written by Neil D. Wilkin
N0060 ! February 2, 1998
N0070 ! Tool 1 K68, 35 deg., length X-5.96875, Z-1.21875
N0080 ! ...Using center of tool, and offset X+_____, Z0
N0090 ! Start machine at X0, Z10.
N0100 ! MDI T0, touch face w/tool 1, MDI W0.71, and set Z-start = P42
N0110 ! If no rough cut to be run, MDI W0.73 and set Z-start = P42
N0120 ! Semifinish feed rate=0.005 in/rev
N0130 ! The semifinish part is 0.01 (0.02 dia) inch oversize
N0140 !
N0150 G70      ! Inches mode
N0160 T0100    ! Select tool at turret home position
N0170 T0       ! Remove tool offsets, after selecting tool
N0180 ! Start Machining here....
N0190 G94 G97 T0 M53  ! In/min, dir rpm, no tool offsets, high spindle range
N0200 M03 S3000      ! Spindle on forward, set speed to 3000 rpm
N0210 G00 X0 Z(P42)  ! Move to Z start
N0220 G92 X30.4 Z2.0 ! Set part zero and max spindle speed
N0230 T0100          ! Apply tool lengths
N0240 G00 X6.2625 Z-4.30875 T0101 M08  ! Go to Start, apply tool offsets; coolant ON
N0250 G00 X6.2625 Z-4.20875 ! Z move to remove backlash
N0260 G04 X5.0       ! Delay for coolant and spindle
N0270 G95            ! Inch per rev mode
N0280 G01 F0.005 X5.30250  Z-4.20875 ! To upper collar
```

```
N0290  G01 X5.30250  Z-3.70875 ! Cut upper collar
N0300  G01 X4.80146 Z-3.70875 ! To start of taper
N0310  G01 X2.38756  Z-1.58486 ! Taper and start of arc
N0320  G02 X0.00000 Z0.04125 F0.005 I-1.19378 K0.37486 ! Cut arc
N0330  G01 X-0.05000 Z0.04125   ! Beyond axis
N0340  G00 Z0.14125  ! Clear part in Z
N0350  G00 X6.2625   ! Clear part in X
N0360  G94              ! Inch per minute mode
N0370  G01 F100.0 X30.4 Z2.0 T00 M05 M09  ! Reset all registers
N0380  G92 X0 Z(P42)   ! Reset register to machine values
N0390  G00 X0 Z10       ! Return home
N0400  M30              ! Rewind
N9999  (END, PROG)
```

### A.4.2.11. Third Part in the PIECS11 Family, Finish Cut Points

Finish cuts.

Diameter = 5.22000

Start

at point 1, X= 6.26250 Z= -4.31875

at point 2, X= 6.26250 Z= -4.21875

at point 3, X= 5.28250 Z= -4.21875

at point 4, X= 5.28250 Z= -3.71875

at point 5, X= 4.78982 Z= -3.71875

at point 6, X= 2.36586 Z= -1.58600

at point 7, X= 0.00000 Z= 0.03125

at point 8, X= -0.05000 Z= 0.03125

arc center X= 0.00000 Z= -1.21000

arc radius 1.24125

arc center offset I = -1.18293 K = 0.37600

### A.4.2.12. Third Part in the PIECS11 Family, Finish Cut Program

```
N0010  (ID,PROG, 370021, Finish Cut: PIECS31)
N0020  ! The following are values to change part size as needed:
N0030  ! Diameter 5.22 program
N0040  ! PIECS31 part -- Aluminum 6061-T6
N0050  ! Designed and written by Neil D. Wilkin
N0060  ! February 2, 1998
N0070  ! Tool 1 K68, 35 deg., length X-5.96875, Z-1.21875
N0080  ! ...Using center of tool, and offset X+_____, Z0
N0090  ! Start machine at X0, Z10.
N0100  ! MDI T0, touch face w/tool 1, MDI W0.71, and set Z-start = P42
N0110  ! If no rough cut to be run, MDI W0.73 and set Z-start = P42
N0120  ! Finish feed rate=0.005 in/rev
N0130  ! The semifinish part is 0.01 (0.02 dia) inch oversize
N0140  !
N0150  G70          ! Inches mode
N0160  T0100        ! Select tool at turret home position
N0170  T0           ! Remove tool offsets, after selecting tool
N0180  ! Start Machining here....
N0190  G94 G97 T0 M53  ! In/min, dir rpm, no tooloffsts, hi spndl range
N0200  M03 S3000       ! Spindle on forward, set speed to 3000 rpm
N0210  G00 X0 Z(P42)   ! Move to Z start
N0220  G92 X30.4 Z2.0  ! Set part zero and max spindle speed
N0230  T0100           ! Apply tool lengths
N0240  G00 X6.2625 Z-4.31875 T0101 M08  ! Add tool offsets; Coolant ON
N0244  (UPD, 1, TOV(X), 0.00000)
N0245  (UPD, 1, TOV(Z), 0.00000)
N0250  G00 X6.2625 Z-4.21875 ! Z move to remove backlash
N0260  G04 X5.0        ! Delay for coolant and spindle
N0270  G95             ! Inch per rev mode
N0280  G01 F0.005 X5.28250  Z-4.21875 ! To upper collar
N0290  G01       X5.28250  Z-3.71875 ! Cut upper collar
N0300  G01       X4.78982  Z-3.71875 ! To start of taper
N0310  G01       X2.36586  Z-1.58600 ! Taper and start of arc
N0320  G02       X0.00000  Z0.03125 F0.005 I-1.18293 K0.37600 ! Arc
N0330  G01       X-0.05000 Z0.03125  ! Beyond axis
N0340  G00 Z0.14125    ! Clear part in Z
N0350  G00 X6.2625     ! Clear part in X
N0360  G94             ! Inch per minute mode
N0370  G01 F100.0 X30.4 Z2.0 T00 M05 M09  ! Reset all registers
N0380  G92 X0 Z(P42)   ! Reset register to machine values
N0390  G00 X0 Z10      ! Return home
/N0400  P42=(P42-0.02)! Decrement part zero for next series of cuts
N0410  M30             ! Rewind
N9999  (END, PROG)
```

### A.4.2.13. Fourth Part in the PIECS11 Family, Semifinish Cut Points

Semifinish cuts.

Diameter = 5.18000

Start

at point 1, X= 6.26250 Z= -4.30875

at point 2, X= 6.26250 Z= -4.20875

at point 3, X= 5.26250 Z= -4.20875

at point 4, X= 5.26250 Z= -3.70875

at point 5, X= 4.77818 Z= -3.70875

at point 6, X= 2.34414 Z= -1.56713

at point 7, X= 0.00000 Z= 0.04125

at point 8, X= -0.05000 Z= 0.04125

arc center X= 0.00000 Z= -1.19000

arc radius 1.23125

arc center offset I = -1.17207 K = 0.37713

### A.4.2.14. Fourth Part in the PIECS11 Family, Semifinish Cut Program

```
N0010 (ID,PROG, 380011, Semifinish Cut: PIECS41)
N0020 ! The following are values to change part size as needed:
N0030 ! Diameter 5.18 program
N0040 ! PIECS41 part -- Aluminum 6061-T6
N0050 ! Designed and written by Neil D. Wilkin
N0060 ! February 2, 1998
N0070 ! Tool 1 K68, 35 deg., length X-5.96875, Z-1.21875
N0080 ! ...Using center of tool, and offset X+_____, Z0
N0090 ! Start machine at X0, Z10.
N0100 ! MDI T0, touch face w/tool 1, MDI W0.71, and set Z-start = P42
N0110 ! If no rough cut to be run, MDI W0.73 and set Z-start = P42
N0120 ! Semifinish feed rate=0.005 in/rev
N0130 ! The semifinish part is 0.01 (0.02 dia) inch oversize
N0140 !
N0150 G70      ! Inches mode
N0160 T0100    ! Select tool at turret home position
N0170 T0       ! Remove tool offsets, after selecting tool
N0180 ! Start Machining here....
N0190 G94 G97 T0 M53  ! In/min, dir rpm, no tool offsets, high spindle range
N0200 M03 S3000      ! Spindle on forward, set speed to 3000 rpm
N0210 G00 X0 Z(P42)   ! Move to Z start
N0220 G92 X30.4 Z2.0  ! Set part zero and max spindle speed
N0230 T0100          ! Apply tool lengths
N0240 G00 X6.2625 Z-4.30875 T0101 M08  ! Go to Start, apply tool offsets; coolant ON
N0250 G00 X6.2625 Z-4.20875 ! Z move to remove backlash
N0260 G04 X5.0       ! Delay for coolant and spindle
N0270 G95            ! Inch per rev mode
N0280 G01 F0.005 X5.26250  Z-4.20875 ! To upper collar
N0290 G01 X5.26250  Z-3.70875 ! Cut upper collar
N0300 G01 X4.77818 Z-3.70875 ! To start of taper
N0310 G01 X2.34414  Z-1.56713 ! Taper and start of arc
N0320 G02 X0.00000 Z0.04125 F0.005 I-1.17207 K0.37713 ! Cut arc
N0330 G01 X-0.05000 Z0.04125   ! Beyond axis
N0340 G00 Z0.14125  ! Clear part in Z
N0350 G00 X6.2625   ! Clear part in X
N0360 G94            ! Inch per minute mode
N0370 G01 F100.0 X30.4 Z2.0 T00 M05 M09  ! Reset all registers
N0380 G92 X0 Z(P42)   ! Reset register to machine values
N0390 G00 X0 Z10       ! Return home
N0400 M30              ! Rewind
N9999 (END, PROG)
```

### A.4.2.15. Fourth Part in the PIECS11 Family, Finish Cut Points

Finish cuts.

Diameter = 5.18000

Start

at point 1, X= 6.26250 Z= -4.31875

at point 2, X= 6.26250 Z= -4.21875

at point 3, X= 5.24250 Z= -4.21875

at point 4, X= 5.24250 Z= -3.71875

at point 5, X= 4.76654 Z= -3.71875

at point 6, X= 2.32240 Z= -1.56824

at point 7, X= 0.00000 Z= 0.03125

at point 8, X= -0.05000 Z= 0.03125

arc center X= 0.00000 Z= -1.19000

arc radius 1.20125

arc center offset I = -1.16120 K = 0.37824

### A.4.2.16. Fourth Part in the PIECS11 Family, Finish Cut Program

```
N0010 (ID,PROG, 380021, Finish Cut: PIECS41)
N0020 ! The following are values to change part size as needed:
N0030 ! Diameter 5.18 program
N0040 ! PIECS41 part -- Aluminum 6061-T6
N0050 ! Designed and written by Neil D. Wilkin
N0060 ! February 2, 1998
N0070 ! Tool 1 K68, 35 deg., length X-5.96875, Z-1.21875
N0080 ! ...Using center of tool, and offset X+_____, Z0
N0090 ! Start machine at X0, Z10.
N0100 ! MDI T0, touch face w/tool 1, MDI W0.71, and set Z-start = P42
N0110 ! If no rough cut to be run, MDI W0.73 and set Z-start = P42
N0120 ! Finish feed rate=0.005 in/rev
N0130 ! The semifinish part is 0.01 (0.02 dia) inch oversize
```

```
N0140 !
N0150 G70          ! Inches mode
N0160 T0100        ! Select tool at turret home position
N0170 T0           ! Remove tool offsets, after selecting tool
N0180 ! Start Machining here....
N0190 G94 G97 T0 M53  ! In/min, dir rpm, no tooloffsts, hi spndl range
N0200 M03 S3000      ! Spindle on forward, set speed to 3000 rpm
N0210 G00 X0 Z(P42)   ! Move to Z start
N0220 G92 X30.4 Z2.0  ! Set part zero and max spindle speed
N0230 T0100        ! Apply tool lengths
N0240 G00 X6.2625 Z-4.31875 T0101 M08  ! Add tool offsets; Coolant ON
N0244 (UPD, 1, TOV(X), 0.00000)
N0245 (UPD, 1, TOV(Z), 0.00000)
N0250 G00 X6.2625 Z-4.21875 ! Z move to remove backlash
N0260 G04 X5.0       ! Delay for coolant and spindle
N0270 G95          ! Inch per rev mode
N0280 G01 F0.005 X5.24250  Z-4.21875 ! To upper collar
N0290 G01       X5.24250  Z-3.71875 ! Cut upper collar
N0300 G01       X4.76654  Z-3.71875 ! To start of taper
N0310 G01       X2.32240  Z-1.56824 ! Taper and start of arc
N0320 G02       X0.00000  Z0.03125 F0.005 I-1.16120 K0.37824 ! Arc
N0330 G01       X-0.05000 Z0.03125  ! Beyond axis
N0340 G00 Z0.14125    ! Clear part in Z
N0350 G00 X6.2625     ! Clear part in X
N0360 G94          ! Inch per minute mode
N0370 G01 F100.0 X30.4 Z2.0 T00 M05 M09  ! Reset all registers
N0380 G92 X0 Z(P42)   ! Reset register to machine values
N0390 G00 X0 Z10      ! Return home
/N0400  P42=(P42-0.02)! Decrement part zero for next series of cuts
N0410 M30          ! Rewind
N9999 (END, PROG)
```

### A.4.2.17. Fifth Part in the PIECS11 Family, Semifinish Cut Points

Semifinish cuts.

Diameter = 5.14000

Start

at point 1, X= 6.26250 Z= -4.30875

at point 2, X= 6.26250 Z= -4.20875

at point 3, X= 5.22250 Z= -4.20875

at point 4, X= 5.22250 Z= -3.70875

at point 5, X= 4.75490 Z= -3.70875

at point 6, X= 2.30064 Z= -1.54934

at point 7, X= 0.00000 Z= 0.04125

at point 8, X= -0.05000 Z= 0.04125

arc center X= 0.00000 Z= -1.17000

arc radius 1.21125

arc center offset I = -1.15032 K = 0.37934

### A.4.2.18. Fifth Part in the PIECS11 Family, Semifinish Cut Program

```
N0010 (ID,PROG, 390011, Semifinish Cut: PIECS51)
N0020 ! The following are values to change part size as needed:
N0030 ! Diameter 5.14 program
N0040 ! PIECS51 part -- Aluminum 6061-T6
N0050 ! Designed and written by Neil D. Wilkin
N0060 ! February 2, 1998
N0070 ! Tool 1 K68, 35 deg., length X-5.96875, Z-1.21875
N0080 ! ...Using center of tool, and offset X+_____, Z0
N0090 ! Start machine at X0, Z10.
N0100 ! MDI T0, touch face w/tool 1, MDI W0.71, and set Z-start = P42
N0110 ! If no rough cut to be run, MDI W0.73 and set Z-start = P42
N0120 ! Semifinish feed rate=0.005 in/rev
N0130 ! The semifinish part is 0.01 (0.02 dia) inch oversize
N0140 !
N0150 G70      ! Inches mode
N0160 T0100    ! Select tool at turret home position
N0170 T0       ! Remove tool offsets, after selecting tool
N0180 ! Start Machining here....
N0190 G94 G97 T0 M53  ! In/min, dir rpm, no tool offsets, high spindle range
N0200 M03 S3000      ! Spindle on forward, set speed to 3000 rpm
N0210 G00 X0 Z(P42)   ! Move to Z start
N0220 G92 X30.4 Z2.0  ! Set part zero and max spindle speed
N0230 T0100          ! Apply tool lengths
N0240 G00 X6.2625 Z-4.30875 T0101 M08  ! Go to Start, apply tool offsets; coolant ON
N0250 G00 X6.2625 Z-4.20875 ! Z move to remove backlash
N0260 G04 X5.0       ! Delay for coolant and spindle
N0270 G95            ! Inch per rev mode
N0280 G01 F0.005 X5.22250  Z-4.20875 ! To upper collar
```

```
N0290  G01 X5.22250  Z-3.70875 ! Cut upper collar
N0300  G01 X4.75490 Z-3.70875 ! To start of taper
N0310  G01 X2.30064  Z-1.54934 ! Taper and start of arc
N0320  G02 X0.00000 Z0.04125 F0.005 I-1.15032 K0.37934 ! Cut arc
N0330  G01 X-0.05000 Z0.04125   ! Beyond axis
N0340  G00 Z0.14125  ! Clear part in Z
N0350  G00 X6.2625   ! Clear part in X
N0360  G94              ! Inch per minute mode
N0370  G01 F100.0 X30.4 Z2.0 T00 M05 M09  ! Reset all registers
N0380  G92 X0 Z(P42)   ! Reset register to machine values
N0390  G00 X0 Z10       ! Return home
N0400  M30              ! Rewind
N9999  (END, PROG)
```

### A.4.2.19. Fifth Part in the PIECS11 Family, Finish Cut Points

Finish cuts.

Diameter = 5.14000

Start

at point 1, X= 6.26250 Z= -4.31875

at point 2, X= 6.26250 Z= -4.21875

at point 3, X= 5.20250 Z= -4.21875

at point 4, X= 5.20250 Z= -3.71875

at point 5, X= 4.74326 Z= -3.71875

at point 6, X= 2.27886 Z= -1.55041

at point 7, X= 0.00000 Z= 0.03125

at point 8, X= -0.05000 Z= 0.03125

arc center X= 0.00000 Z= -1.17000

arc radius 1.20125

arc center offset I = -1.13943 K = 0.38041

### A.4.2.20. Fifth Part in the PIECS11 Family, Finish Cut Program

```
N0010 (ID,PROG, 390021, Finish Cut: PIECS51)
N0020 ! The following are values to change part size as needed:
N0030 ! Diameter 5.14 program
N0040 ! PIECS51 part -- Aluminum 6061-T6
N0050 ! Designed and written by Neil D. Wilkin
N0060 ! February 2, 1998
N0070 ! Tool 1 K68, 35 deg., length X-5.96875, Z-1.21875
N0080 ! ...Using center of tool, and offset X+_____, Z0
N0090 ! Start machine at X0, Z10.
N0100 ! MDI T0, touch face w/tool 1, MDI W0.71, and set Z-start = P42
N0110 ! If no rough cut to be run, MDI W0.73 and set Z-start = P42
N0120 ! Finish feed rate=0.005 in/rev
N0130 ! The semifinish part is 0.01 (0.02 dia) inch oversize
N0140 !
N0150 G70          ! Inches mode
N0160 T0100        ! Select tool at turret home position
N0170 T0           ! Remove tool offsets, after selecting tool
N0180 ! Start Machining here....
N0190 G94 G97 T0 M53  ! In/min, dir rpm, no tooloffsts, hi spndl range
N0200 M03 S3000      ! Spindle on forward, set speed to 3000 rpm
N0210 G00 X0 Z(P42)  ! Move to Z start
N0220 G92 X30.4 Z2.0  ! Set part zero and max spindle speed
N0230 T0100          ! Apply tool lengths
N0240 G00 X6.2625 Z-4.31875 T0101 M08  ! Add tool offsets; Coolant ON
N0244 (UPD, 1, TOV(X), 0.00000)
N0245 (UPD, 1, TOV(Z), 0.00000)
N0250 G00 X6.2625 Z-4.21875 ! Z move to remove backlash
N0260 G04 X5.0       ! Delay for coolant and spindle
N0270 G95            ! Inch per rev mode
N0280 G01 F0.005 X5.20250  Z-4.21875 ! To upper collar
N0290 G01       X5.20250  Z-3.71875 ! Cut upper collar
N0300 G01       X4.74326  Z-3.71875 ! To start of taper
N0310 G01       X2.27886  Z-1.55041 ! Taper and start of arc
N0320 G02       X0.00000  Z0.03125 F0.005 I-1.13943 K0.38041 ! Arc
N0330 G01       X-0.05000 Z0.03125  ! Beyond axis
N0340 G00 Z0.14125    ! Clear part in Z
N0350 G00 X6.2625     ! Clear part in X
N0360 G94             ! Inch per minute mode
N0370 G01 F100.0 X30.4 Z2.0 T00 M05 M09  ! Reset all registers
N0380 G92 X0 Z(P42)   ! Reset register to machine values
N0390 G00 X0 Z10      ! Return home
/N0400  P42=(P42-0.02)! Decrement part zero for next series of cuts
N0410 M30             ! Rewind
N9999 (END, PROG)
```